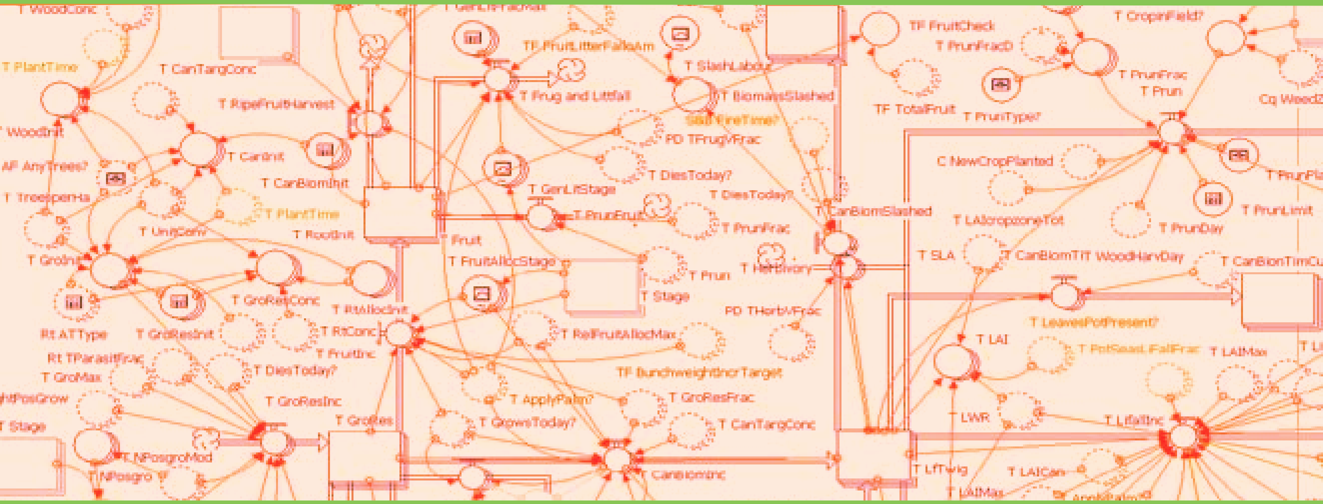
Meine van Noordwijk, Betha Lusiana, Ni’matul Khasanah, Rachmat Mulia

WaNuLCAS 4.0

Background on a model of

Water, Nutrient and Light Capture in Agroforestry System



World Agroforestry Centre

WaNuLCAS 4.0

Background on a model of Water, Nutrient and Light Capture in Agroforestry Systems

Meine van Noordwijk
Betha Lusiana
Ni'matul Khasanah
Rachmat Mulia

World Agroforestry Centre
TRANSFORMING LIVES AND LANDSCAPES

INTERNATIONAL CENTRE FOR RESEARCH IN AGROFORESTRY

Correct citation:

Van Noordwijk M, Lusiana B, Khasanah N and Mulia R. 2011. WaNuLCAS version 4.0, Background on a model of water nutrient and light capture in agroforestry systems. Bogor, Indonesia. World Agroforestry Centre - ICRAF, SEA Regional Office. 224 p.

Copies of the software available freely from the web:
http://www.worldagroforestrycentre/sea
More information can be obtained by correspondence to:
M.van-Noordwijk@cgiar.org and/or B.Lusiana@cgiar.org and/or N.Khasanah@cgiar.org

Related journal publication (based on version 1.0)
Van Noordwijk, M. and Lusiana, B., 1999 WaNuLCAS, a model of water, nutrient and light capture in agroforestry systems. Agroforestry Systems 43: 217-242

ISBN 978-979-3198-59-0

Disclaimer and copyright

This is a third release of a general model of tree-soil-crop interactions in agroforestry. Although efforts have been made to incorporate relevant process knowledge on a range of interactions, the model is not more (and not less) than a research tool. Model predictions may help in developing specific hypotheses for research, in exploring potential management options and extrapolation domains, but they should not be used as authoritative statements per se.

Layout by:
Sadewa

Cover artwork:
Tikah Atikah

World Agroforestry Centre
Jl. CIFOR, Situ Gede, Sindang Barang, Bogor 16115
PO Box 161, Bogor 16001, Indonesia

Acknowledgements

This publication is an updated manual for WaNuLCAS version 4.0. The content of this manual largely based from version 2.0 and 3.01.

The authors wish to acknowledge valuable inputs and advice from many colleagues over the last four years. Earlier versions of the WaNuLCAS model and manual were used by a number of users and this lead to valuable feedback:

- Dr. Jules Bayala, Dr. Catherine Muthuri, Dr. Simone Radersma and Dr. Didik Suprayogo have contributed to specific model sectors.
- Dr. Luis Fernando Guedes-Pinto, Johan Iwald, La Nguyen, Lina Nolin, Vincent Cheylan have provided useful comments and feedback that was built into the current version.
- Previous manual and model version have received valuable feedbacks from Dr. Peter de Willigen (AB-DLO Haren, the Netherlands) and Dr. Georg Cadish (Wye College, UK) in the context of the Biological Management and Soil Fertility (BMSF) Project. Dr. Richard Coe, Dr Quirine Ketterings and Dr. Edwin Rowe have also contributed to specific model sectors.
- The feedback of all trainings and courses participants in UK (Agroforestry Modelling Project funded by Forestry Research Program/DFID-FRP), Bogor, Bandar Lampung, Chiang Mai, Claveria, Guadaloupe, Los Banos, Malang, Nairobi, and Turrialba, Nanyuki are gratefully acknowledged.

Table of Content

List of Figures

List of Tables

Chapter 1

Introduction and Objectives

This background document is written for two groups of readers:

1. *Agroforestry researchers who are not very familiar with modelling or with quantitative descriptions of resource capture in agroforestry, but who may be tempted to use the model as part of their toolbox, for exploring new variants of agroforestry system before they embark on field experimentation,*
2. *Modellers who know little about agroforestry but a lot about component processes and who may find in WaNuLCAS a framework for exploring the system context of their favoured aspect of tree-soil-crop interactions.*

The text of this background documentation is organized as follows:
Chapter 1*: discusses some general considerations about agroforestry modelling which have lead to the development of WaNuLCAS,*
Chapter 2*: sketches an outline of the program to provide an overview of the components and the possibilities for use,*
Chapter 3*: gives a more detailed account, sector by sector of the specific assumptions made for the model and of the options provided for the model user,*
Chapter 4*: gives a number of worked-out examples of model applications*
The appendices *give detailed instructions on how to get the model started, suggest exercises to familiarize oneself with the model and provide descriptions of the model parameters.*

1.1. Balancing pattern and process

A focal point in the analysis of where and how agroforestry systems work is still whether or not tree-crop systems can utilize resources of light, water and/or nutrients which would not be used in a simpler tree or crop system (Cannell *et al.*, 1996). A fair amount of detail in the description of above- and belowground resource capture by the component species is needed to evaluate both competition and complementarity (Sanchez, 1995; Ong and Huxley, 1996).

Tree-soil-crop interactions occur both in space and time. In 'sequential' agroforestry systems neighbourhood effects in a landscape mosaic still have a spatial element, while 'simultaneous' systems often have at least an element of zonation. The dichotomy between sequential and simultaneous agroforestry systems may thus have been overstated in the past and a modelling framework is desirable in which they are endpoints of a continuum.

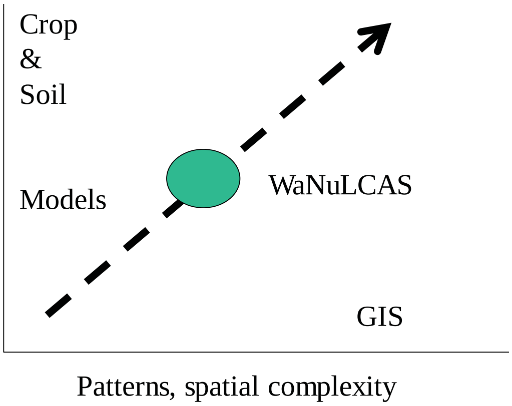


Figure 1.1. Schematic classification of the way crop growth models deal with spatial and temporal complexity; agroforestry models should explore the diagonal, rather than try to introduce spatial patterns in complex process based models.

In modelling agroforestry systems, a balance should be maintained between 'process' and 'pattern', between temporal and spatial aspects (Figure 1.1). Existing crop growth models tend to be detailed in 'processes', but they usually do not take spatial patterns into account. They (implicitly) assume a homogeneous 'minimum representative' area, with a one-dimensional variation between soil layers. Most GIS (geographical information systems) applications do not incorporate spatial interactions and estimate the total output of an area as the summation of area times output per unit area, for grid cells which are not dynamically interacting with their neighbours (similar to a 'stratified' sampling approach). For representations of agroforestry we need both spatial and dynamic aspects, and should therefore aim at models along the diagonal line in Figure. 1.1. Full-scale detail on spatial interactions may not be achievable for any reasonable process description, however, and it may be best to start in the lower left corner with fairly simple process and spatial descriptions, only to move to the upper right corner where research questions require more detail. As a starting point on the spatial side, we have chosen for a system of 'zoning', which can relate many types of spatial patterns to a model still covering essential aspects of real-world behaviour. Spatial interactions, such as shading aboveground and competition for water and nutrients belowground may occur over a range of distances. Instead of a black/white sharp boundary, every tree-crop interface may consist of several shades of grey in between. The zoning system we opt for appears to have the minimum complexity to do justice to such interactions.

In simultaneous agroforestry systems, trees and food crops are interacting in various ways. As both positive and negative interactions occur, optimization of the system will have to be site specific. The most important interactions probably are:

1. Shading by the trees, reducing light intensity at the crop level,
2. Competition between tree and crop roots for water and/or nutrients in the topsoil,
3. Mulch production from the trees, increasing the supply of N and other nutrients to the food crops,
4. Nitrogen supply by tree roots to crop roots, either due to root death following tree pruning or by direct transfer if nodulated roots are in close contact with crop roots,
5. Effects on weeds, pests and diseases,
6. Long term effects on erosion, soil organic matter content and soil compaction.

Interactions 3, 4 and 6 are positive, 1 and 2 are normally negative, and 5 can have both positive and negative elements. The positive and negative effects can interact during the growing season, and this may limit the use of end-of-season summaries of the tree-crop interaction effects. Yet, such summaries are helpful as a first approximation.

1.2. Tree-soil-crop interactions

The success of any intercropping depends on the balance of positive (facilitation) and negative (competition) interactions between the components Vandermeer (1989). Ong (1995) and Akeampyong *et al*. (1995) developed a simple equation for quantifying tree-soil-crop interactions (I), distinguishing between positive effects of trees on crop growth via soil fertility improvement (F) and negative effects via competition (C) for light, water and nutrients. Very much simplified, the interaction term is positive and the combined system may make sense if $F > C$, and not if $F < C$.

Cannell *et al*. (1996) attempted to clarify the resource base of the production by both the crop and the tree. Part of the 'fertility' effect of the tree is based on light, water and nutrient resources which the tree acquired in competition with the crop (F_{comp}); another part may have been obtained in complement to resources available for the crop ($F_{noncomp}$). Similarly, part of the resources acquired by the tree in competition with the crop is recycled within the system and may thus be used by a future crop (C_{recycl}). Tree products that are not recycled may have direct value for the farmer ($C_{nonrecycl}$).

One may argue that F_{comp} is based on the same resources as C_{recycl} and that in the longer run the two terms would cancel. The question whether or not a tree-crop combination gives yield benefits then depends on:

1. the complementarity of the resource use,
2. the value of direct tree products, specifically those obtained in competition, $C_{nonrecycl}$, relative to the value of crop products that could have been produced with these resources.
3. the efficiency of recycling tree resources into crop products, specifically for the resources obtained in co mpetition with the crop, C_{recycl}.

Table 1.1. Three-step approach to analysis and synthesis of tree-soil-crop interactions in simultaneous agroforestry systems. A direct experimental separation of the terms in the equation is combined with quantification of key processes and followed by model synthesis to explore management options and system-site matching (van Noordwijk *et al*., 1998a).

$Y_c =$ Crop yield in interaction	$Y_0 +$ Crop yield in monoculture	$F_1 +$ Direct fertility effect	$F\omega +$ Long term fertility effect	$C_l +$ Competition for light	$C_{w+n} +$ Competition for water and nutrients	**M** Micro-climate effects
1. Experimental		Mulch transfer	Residual effect	Tree removal	Root barriers	
2. Process-level understanding		Litter quality, mineralization rates	Functional SOM fractions (Ludox)	Canopy shape, light profiles	Root architecture (fractal branching analysis)	
3. Synthesis model		WaNuLCAS				

Apart from yield effects of agroforestry, labour requirements have a strong impact on profitability, and for this one should compare additional labour use (eg. tree pruning) and labour saving aspects (eg. weed control). Complementarity of resource use can be based on a difference in timing of tree and crop resource demand. If the tree picks up the 'left overs' from the cropping period, as occurs with water in the *Grevillea* maize systems in Kenya (Ong; *pers. comm*.) and transforms these resources into valuable products, a considerable degree of competition during the temporal overlap may be acceptable to the farmer. If tree products have no direct value, agroforestry systems may only be justified if $F_{noncomp} > C_{nonrecycl}$. With increasing direct value of the tree products, the requirements for complementarity decrease.

The efficiency of recycling will depend on the degree of synchrony between mineralization from these organic residues and crop nutrient demand, as well as on the residence time of mineral nutrients in the crop root zone under the site-specific climate and soil conditions (De Willigen and Van Noordwijk, 1989; Myers *et al*., 1994, 1997).

As light is not stored in ecosystems, complementarity in light use is easy to measure. For water and nutrients complementarity has to consider time scales linked to the 'residence' times of the resources in the ecosystem; residence times tend to increase from water, via nitrogen and potassium to phosphorus. For P resources used by the tree it will be difficult to measure whether or not this P might have become available to the crop in the absence of trees. Indications of complementarity in belowground resource use can be obtained by observing the root distribution of both components. Actual uptake of resources will, however, depend on resource and root distribution as well as demand factors, and thus the degree of overlap in root distribution per se is not sufficient to predict competition.

Van Noordwijk (1996a) presented explicit algebraic solutions for an agroforestry model which links both the mulch production and its ensuing soil fertility effect and the shading which is assumed to have a negative effect on crop yields to the biomass production of the tree. The model leads to a simple mulch/shade ratio as a basis for comparing tree species. The model also predicts that at low soil fertility, where the soil fertility improvement due to mulch can be pronounced, there is more chance that an agroforestry system improves crop yields than at higher fertility where the negative effects of shading will dominate. The mulch/shade model, however, does not incorporate the interactions between water availability, N dynamics, crop and tree growth. Incorporating these elements on the basis of a daily time step extends the model beyond what can be solved explicitly and into the realm of dynamic simulation models, which keep track of resource stocks outside and inside the plants and use these to calculate daily resource flows and daily resource capture.

The tree-soil-crop interaction equation can be further analyzed by differentiating between short and long term fertility effects (F_1 and $F\omega$, respectively) and by separating the competition term in an above- and a belowground component (C_l and C_{n+w}, respectively). Van Noordwijk *et al*. (1998a) described a three-step approach to link these overall terms to experimental treatments, process research and WaNuLCAS as a synthesis model (Table 1.1). The total balance for belowground resources (water or nutrients) inputs into an agroforestry system is:

$$\Delta Stored = Input + Recycle - Upt_{crop} - Upt_{tree,comp} - Upt_{tree,noncomp} - Loss \qquad \textbf{[1]}$$

The term $Upt_{tree,noncompetitive}$ represents the safetynet function of tree roots for nutrients and water leaching and percolating below the zone of crop roots and/or outside of the crop growing season (Van Noordwijk *et al*., 1996), as well as a nutrient pump role for resources stored in the subsoil for longer periods of time (Young, 1997).

Table 1.2. Representation of resource capture (equation 1) in a simple tree-crop agroforestry system, where the crop roots are confined to the 'topsoil' and the tree roots explore the 'subsoil' as well; the subscripts 1, 2 and 3 refer to crop zones with increasing distance to the tree.

Term in eq. 1	Water	Nitrogen	Light
Input	Rainfall, irrigation runon-runoff	Fertilizer & organic imports	Sum of daily radiation
Recycle	Hydraulic lift into crop root zone	Litterfall, tree prunings, crop residues	-
$Uptake_{Crop}$	∑W_Uptakecrop	N_fix(Crop) + ∑N_Uptakecrop	∑Lightcap_crop
$Uptake_{Tree,Competitive}$	$\sum_{sub}$W_Uptaketree	$\sum_{top}$N_Uptaketree	$\sum Lightcap\_tree_{1,2}$
$Uptake_{Tree,Noncomp}$	$\sum_{sub}$W_Uptaketree	N_fix(Tree) + $\sum_{sub}$N_Uptaketree	$Lightcap\_tree_3$
Losses	∑Percolation from lowest zone	∑Leaching from lowest zone	1 - ∑Lightcap
Δstorage	ΔWater content	Δ(Nmin & SOM)	-

In summary, we argue that agroforestry systems do not make much sense from a biophysical point of view, unless there is at least some complementarity in resource capture. Direct empirical approaches to quantify complementarity are possible for aboveground processes, but more complex belowground, as resources there are stored over a longer period of time, making it more difficult to judge whether or not resources could have been used outside an agroforestry context. Models of tree-soil-crop interactions have to pay specific attention to the depth from which each component is capturing water and nutrients on a daily basis, in order to derive overall complementarity on a seasonal basis.

1.3. Intercropping, crop-weed and agroforestry models

Attempts to link separately developed crop models into an 'intercropping' model have not been very successful yet (Caldwell *et al.*, 1996). A possible reason for this is that accurate description of both above- and below ground resource capture is more critical in a competitive situation than in a monoculture. Aboveground canopy structure does not matter in a monoculture as long as total LAI is predicted correctly. A coarse approximation of the allocation of current uptake of water and nutrients from the soil profile can be good enough, if the resources not used today still remain in the soil on the next day. In a competitive situation, however, it matters where the leaves of each component are relative to those of other components; belowground resources not utilized today may have been taken up by other components before tomorrow. It thus appears that a reasonable performance of a crop growth model in a monoculture situation is a necessary condition for expecting it to perform in intercropping, but not a sufficient condition. Additional detail may be needed to get above- and belowground resource capture correct.

Kropff and Van Laar (1993) gave an overview of models for crop-weed interactions: such models tend to emphasize the phenology of the species competing for resources, as they are meant to help in predicting the effect of interventions (weeding) at different points in the crop life cycle. Otherwise, crop-weed models differ only in name from intercropping models, as both describe resource capture in a system where at least two plants are interacting.

In intercropping models, however, both components have direct value to the farmer, whereas in crop-weed systems the 'weeds' have no direct value at all (although they may help in conserving nutrients in the system and reducing losses by leaching). Agroforestry models have to include a two-plant interaction (Figure. 1.2), similar to intercropping and crop-weed models, but differ in that one of the plants is a perennial species. Part of the inspiration for an agroforestry model may thus come from existing tree or forest models.

Rather than linking existing tree and crop models, an alternative approach is to develop a generic plant-plant interaction model. The focus should be on above- and belowground resource capture and its interplay (Figure. 1.3). Specific parameters for each component can be derived from more specialized component models, such as drivers for physiological development (onset of flowering, internal redistribution in generative stage). The model should, however, give a fair description of 'architecture' (spatial distribution of the relevant organs) above- and belowground and their consequences for uptake. A correct account of the spatial distribution of organs for resource capture is probably more important in plant-plant interaction models than it is in models for monocultural stands.

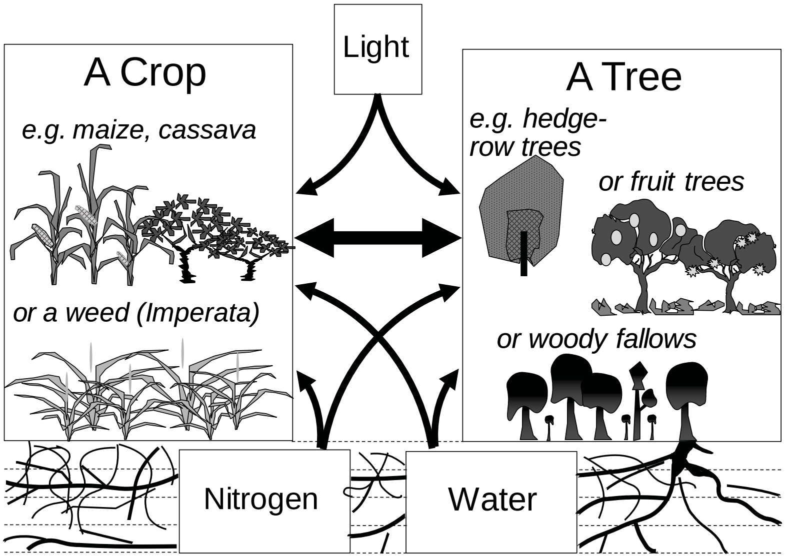


Figure 1.2. Components of the WaNuLCAS model.

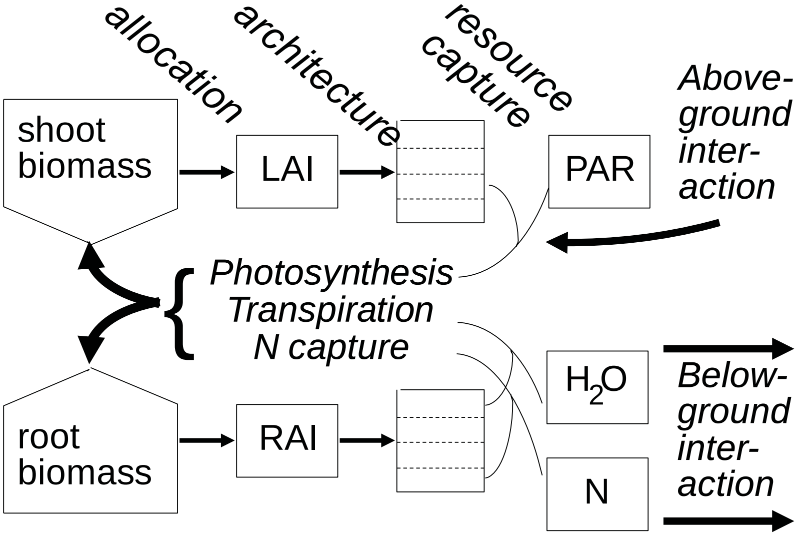


Figure 1.2. Resource capture framework for modeling plant growth, based on shoot and root biomass, allocation to leaf and root area index (LAI and RAI, respectively) and its spatial distribution (based on 'architecture') and capture of light, water and nutrients; aboveground plant-plant interactions modify resource flow, belowground they modify stocks.

A major problem in linking a number of single-species resource capture models into a multi-species resource capture model with a single accounting systems for the resources, is one of priority assignment in the calculation sequence. Models which consistently assign priority to one of the components may vastly overestimate its resource capture, while the solution of some models of alternating priorities is not very satisfactory either (Caldwell *et al*., 1996).

For a more balanced approach, the resource capture of the various components should be further integrated and applied simultaneously, avoiding priority assignment. One way of doing this is adding the root (for water and nutrients) and leaves in a common layer or zone, calculating a total resource capture and sharing this out over the two (or more) components in proportion to their root length density or leaf area. As resource capture is in most cases a non-linear function of root length or leaf area, this approach to resource sharing gives a different result from adding resource capture for the two components (the latter may overestimate potential uptake rates).

1.4. Objectives of the WaNuLCAS Model

In developing a generic model for water, nutrient and light capture in agroforestry systems (WaNuLCAS), we aimed at a model which would:

1. integrate knowledge and hypotheses on below and aboveground resource capture by trees and crops (or any two (or more) types of plants) **at patch scale** (the smallest 'self-contained' unit for describing the tree/crop interaction) as a basis for predicting **complementarity and competition**,
2. build on **well-established modules (models)** of a soil water, organic matter and nitrogen balance, and crop and a tree development to investigate interactions in resource capture,
3. describe the **plant-plant interaction** term as the outcome of **resource capture** efforts by the component species, as determined by their above- and belowground architecture (spatial organization) as well as physiology,
4. be applicable to spatially zoned **agroforestry systems** as well as rotational systems,
5. avoid where possible the use of parameters which can only be derived by fitting the model to empirical data sets and maximize the use of parameters which can be **independently measured**
6. be flexible in exploring **management options** within each type of agroforestry system,
7. be useful in estimating **extrapolation domains** for 'proven' agroforestry techniques, as regards **soil and climate** properties, as well as tree and crop architecture,
8. **be user-friendly** and allow 'non-modelers' to explore a range of options, while remaining **open to improvement** without requiring a complete overhaul of the model,
9. generate **output** which can be used in existing spreadsheets and graphical software,
10. make use of readily available and tested modeling software.

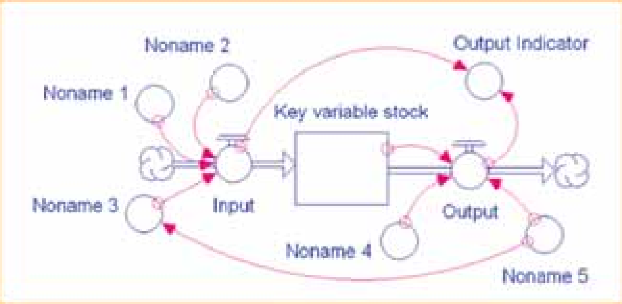
In view of objectives 8, 9 and 10 we chose the **STELLA** Research modeling shell (Hannon and Ruth, 1994) linked to Excel spreadsheets for data input and output. The current model should be seen as a prototype; in the **STELLA** environment it is relatively easy to modify or add modules or relationships.

Models can be of value ('validated' in the original sense of the word) if a) they adequately reflect the major assumptions one would like to make about component processes, if b) they operate smoothly in the parameter range where one would like to use them, and/or if c) their quantitative predictions agree with measured results in specific experiments (Van Noordwijk, 1996b). Before model validation is undertaken, (1) the purpose of the model, (2) the performance criteria and (3) the model context must be specified (Rykiel, 1996). At this stage we have concentrated on levels a and b of the validation process. WaNuLCAS model is meant as a prototype model, not including all possible tree-soil-crop interaction relationships that one can imagine, but incorporating a core of relations which we are fairly sure of for each specific case. In this sense the model can be viewed as a 'null model' (Gotelli and Graves, 1996) which can be used like a null hypothesis as a background against which specific data sets can be tested. The open modeling frame will allow users to add other relationships when and where they wish. Muetzelfeldt and Taylor (1997) have translated WaNuLCAS into a new modelling platform Agroforestry Modeling Environment (AME) as a platform. This modelling environment is now called SIMILE and is currently used in developing FLORES model. The European sylvo-arable agroforestry project SAFE is developing a model with greater spatial articulation HiSAFE.

Further information on agroforestry models can be found on the following web sites:
http://www.montpellier.inra.fr/safe/ for news on the HiSAFE model currently under development
http://www.wiz.uni-kassel.de/ecobas.html for database of ecological models
http://www.ierm.ed.ac.uk/simile/ for SIMILE – previously named AME – Agroforestry Modelling Environment
http://simulistics.com/projects/flores/ for FLORES model
http://www.forestresearch.co.nz/topic.asp?topic=AEM&title=Agroforestry%20Estate%20Model for Agroforestry Estate Model, a Windows application which projects physical and financial yields for an agroforestry project

Intermezzo: Plant -- a first exploration of a dynamic plant growth model in the STELLA environment

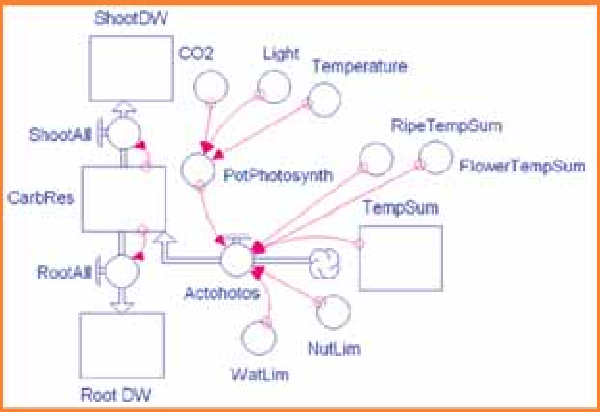
In making a simulation model you can start with an empty sheet of paper or screen, draw a key variable in the centre, consider its inputs and outputs, and the various influences on those inputs and outputs…:



You may realize that you are specifically interested in the 'efficiency' or rate of output per rate of input of the key variable, so this becomes your main output indicator. On further thought, one of factors that is influenced by the 'output' has a feed-back effect on one of the influences on the 'input'. The conceptual model starts to grow, and it becomes a little complex to imagine how the overall output indicator will respond to the various influences that you have recognized. You may want to see it change before your eyes. Wait, we cannot run the model yet, as we first have to specify what these red arrow mean: influences on a process need to be combined in the form of an 'equation'.

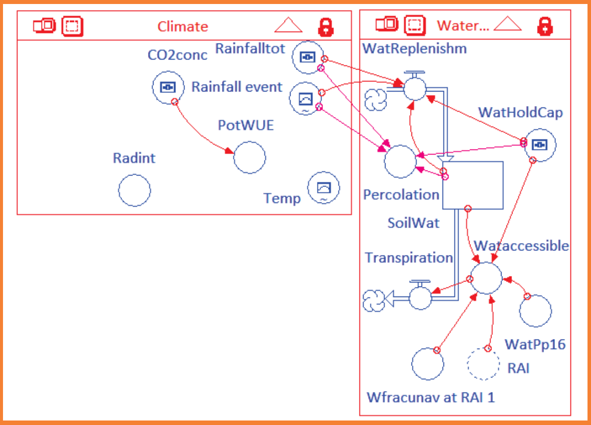
In a nutshell, the above process describes how a model such as WaNuLCAS started. But it has grown so complex that the origin is difficult to trace. In the following description of a basic 'PLANT' model, we introduce a couple of key concepts that are used in more elaborate form in the tree-soil-crop interaction model. PLANT follows the day-to-day development of a plant with leaves, roots, flowers and seeds. The plant takes up water from the soil, that comes from a stock of 'available water' replenished by rainfall. The plant also takes up and thus depletes a stock of soil nutrients. Its rate of photosynthesis is the prime driver of all growth, and requires the combination of light, atmospheric CO_2, stomata that can be open (so water stress shouldn't be too severe) and leaves that are green (so there is enough nitrogen and other nutrients to make the required enzymes and cell structures).

In describing how plants grow we can thus start with the concept of 'photosynthesis' that generates carbohydrate reserves that can be used to make either 'shoot' or 'root' tissues and adds to their dry weight. We can distinguish between a potential rate of photosynthesis that depends on factors such as CO_2 concentration, light and temperature, and an actual one, that can be reduced by water or nutrient stress. An important thing to consider is the development of the plant from vegetative to generative (flowering and fruit production) phases – we may be able to link this 'phenological development' to a temperature-sum that keeps track of the past weather, plus parameters for the thresholds of flowering and fruit(seed) ripeness.

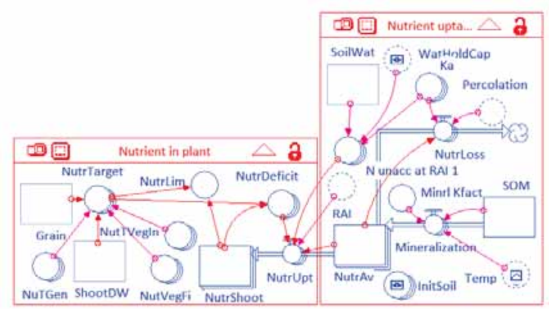


Hey, we're missing something important. Photosynthesis depends on the green leaf area exposed to light – so we need to relate the 'dry weight of shoot' to the leaf area available. Similarly, we need to specify how root dry weight is related to the WatLim and NutLim parameters that describe growth-limiting degrees of water and nutrient stress....

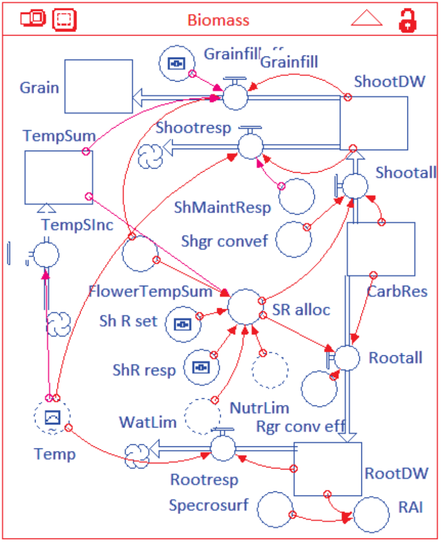
That means we need to add a stock that represents soil water and is replenished by rainfall.



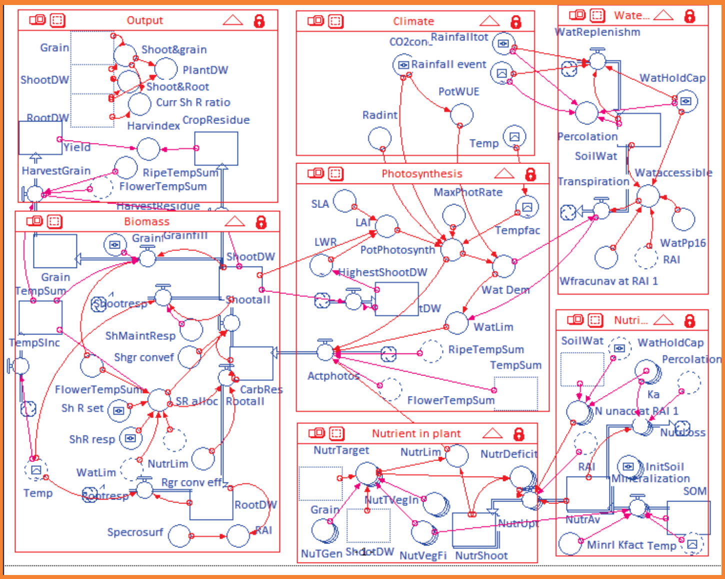
We also need to keep track of the pool of available nutrients in the soil, that can increase through ‘mineralization’ and be reduced by ‘nutrient losses’.



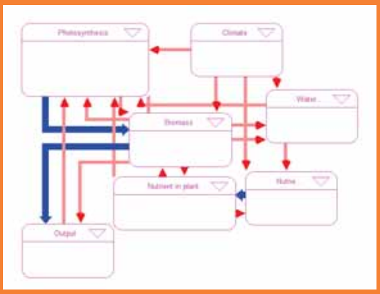
Finally, the basic allocation of available growth reserves in the plant over ‘shoot’ and ‘root’ tissue needs to be specified. A simple rule, consistent with the ‘Functional Equilibrium’ theory developed by the plant physiologist Rienk Brouwer in the early 1960’s is that under water and nutrient stress the plant will allocate more of its resources to ‘root growth’, and in the absence of such stresses allocates mostly to aboveground tissues (leaves or fruits). Our simple plant model thus has a dynamic ‘SR alloc’ or shoot:root allocation parameter, that responds to a genetically determined set point, the current severity of water and nutrient limitations, and to the phonological development. After the onset of flowering the plant will focus its resource allocation on seed production (we use the rather restrictive term ‘grain’ here).



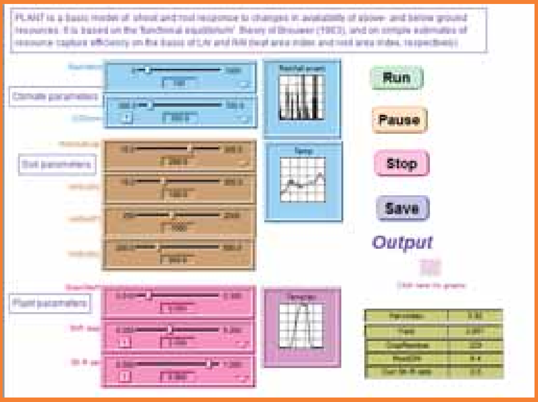
After adding these other stocks and flows, our ‘simple model’ starts to look complicated, but it is now possible to ‘run’ it, as we have specified all relationships.



Finally, we go the ‘upper’ screen and add some sliders for easy modification of input parameters, graphs for daily rainfall and temperature input, and buttons for run control. As outputs there is a stack of graphs and indicators of some of the ratios such as current shoot: root ratio and harvest index. The model is there to be explored, improved, used, expanded



Sector map



Control Screen

Chapter 2

Overview of the Model

Before we give a detailed description of model assumptions and formulation in chapter 3, we will give an overview of the model here .

The model is formulated in the **STELLA** *Research modeling environment and thus remains open to modifications. Emphasis is placed on belowground interactions, where competition for water and nutrients (nitrogen and phosphorus) is based on the effective root length densities of both plant components and current demand by tree and crop.*

Simulations require the prior definition of a soil profile and its soil physical and chemical properties per layer, of a degree of slope and hence lateral interactions, and of the climate.

Agroforestry systems are defined on the basis of spatial zones and a calendar of events for each zone, including growing and harvesting trees or crops, fertilizer use or slash-and-burn land clearing.

2.1. Model features

A key feature of the model is the description of uptake of water and nutrients (N and P) on the basis of root length densities of the tree(s) and the crop, plant demand factors and the effective supply by diffusion at a given soil water content. De Willigen and Van Noordwijk (1994) and Van Noordwijk and Van de Geijn (1996) described underlying principles.

The model was developed to emphasize the common principles underlying a wide range of tree-crop agroforestry systems in order to maximize the cross-fertilization between research into these various systems and explore a wide range of management options. The model can be used for agroforestry systems ranging from hedgerow intercropping (alley cropping) on flat or sloping land (contour hedgerow intercropping), taungya-type transitions into tree-crops, via (relay-planted) fallows to isolated trees in parkland systems. Figure 2.1A and Figuer 2.1B shows the different modules available inside WaNuLCAS model.

Agroforestry systems. The model represents a four-layer soil profile, with four spatial zones, a water, nitrogen and phosphorus balance and uptake by a crop (or weed) and up to three (types of) tree(s). The model can be used both for simultaneous and sequential agroforestry systems and may help to understand the continuum of options ranging from ‘improved fallow’ via relay planting of tree fallows to rotational and simultaneous forms of ‘hedgerow intercropping’. The model explicitly incorporates management options such as tree spacing, pruning regime and choice of species or provenance. The model includes various tree characteristics, such as root distribution, canopy shape, litter quality, maximum growth rate and speed of recovery after pruning.

If applied to hedgerow intercropping, the model allows for the evaluation of different pruning regimes, hedgerow tree spacing and fertilizer application rates. When applied to rotational fallow systems, the ‘edge’ effects between currently cropped parts of a field and the areas where a tree fallow is growing can be simulated. For isolated trees in parkland systems, equidistant zones around individual trees can be ‘pooled’ and the system as a whole can be represented by a number of circles (of different radius) with a tree in the middle (further explanation is given in section 3.1).

Climate effects are mainly included via daily rainfall data, which can be either read from a spreadsheet or generated on the basis of daily probability of rainfall and a division between ‘heavy’, and ‘light’ rains. Average temperature and radiation are reflected in ‘potential’ growth rates. ‘Thermal time’ is reflected in the speed of phenological development. Soil temperature is explicitly used as a variable influencing decomposition and N and P mineralization.

Soil is represented in four layers, the depth of which can be chosen, with specified soil physical properties and initial water and nitrogen contents.

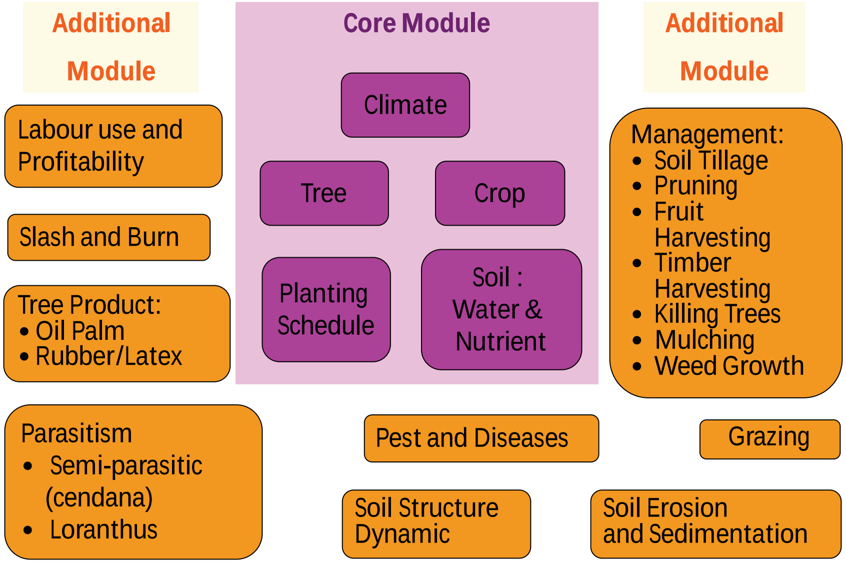


Figure 2.1A. Schematic diagram of different modules.

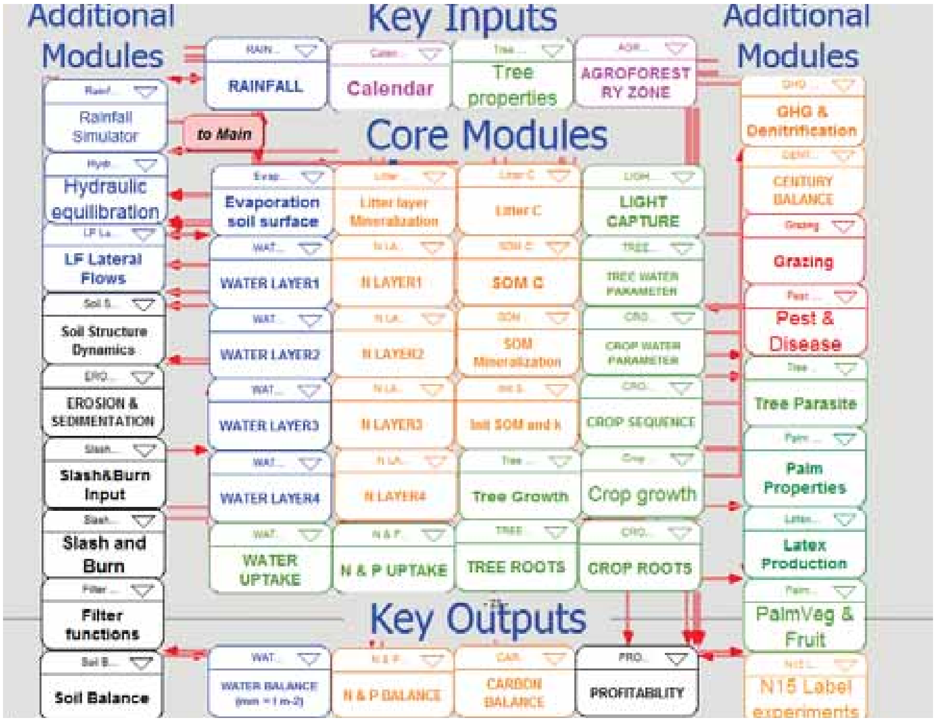


Figure 2.1B. Schematic diagram of different modules inside WaNuLCAS model.

The Water balance of the system includes rainfall and canopy interception, with the option of exchange between the four zones by run-on and run-off as well as subsurface lateral flows, surface evaporation, uptake by the crop and tree and leaching. Vertical as well as horizontal transport of water is included; an option is provided to incorporate (nighttime) 'hydraulic equilibration' via the tree root system, between all cells in the model.

The Nitrogen and Phosphorus balance of the model includes inputs from fertilizer (specified by amount and time of application), atmospheric N fixation, mineralization of soil organic matter and fresh residues and specific P mobilization processes. Uptake by crop and tree is allocated over yields (exported from the field/ patch) and recycled residues. Leaching of mineral N and P is driven by the water balance, the N concentrations and the apparent adsorption constant in each layer, thus allowing for a 'chemical safety net' by subsoil nutrient (incl. nitrate) adsorption.

Growth of both plants ('crop' and 'tree') is calculated on a daily basis by multiplying potential growth (which depends on climate) with the minimum of three 'stress' factors, one for shading, one for water limitation, one for nitrogen and one for phosphorus. For trees a number of allometric equations (which themselves can be derived from fractal branching rules) is used to allocate growth over tree organs.

Uptake of both water and nutrients by the tree and the crop is driven by 'demand' in as far as such is possible by a zero-sink uptake model on the basis of root length density and effective diffusion constants:

$$uptake = \min(\text{demand}, \text{potential uptake}) \qquad \textbf{[2]}$$

For water the potential uptake at a given root length density and soil water content is calculated from the matric flux potential of soil water.

Demand for nitrogen uptake is calculated from empirical relationships of nutrient uptake and dry matter production under non-limiting conditions[1], a 'luxury uptake'[2] a possibility for compensation of past uptake deficits and an option for N fixation (driven by the Ndfa parameter, indicating the part of the N demand which can be met from atmospheric fixation).

Competition for water and nutrients is based on sharing the potential uptake rate for both (based on the combined root length densities) on the basis of relative root length multiplied by relative demand:

$$PotUpt(k) = min\left[\frac{Lrv(k)\,xDemand(k)\,xPotUpt(\sum lrv)}{\sum_{k=1}^{n}\big(Lrv(k)\,xDemand(k)\big)}, PotUpt\big(Lrv(k)\big)\right] \qquad \textbf{[3]}$$

where PotUpt gives the potential uptake rate for a given root length density L_{rv}.

---

[1] The assumptions are 5% N in dry matter up to a closed crop canopy (s reached at an aboveground biomass of about 2 Mg ha-1) and 1%N in new dry matter after that point with target N:P ratio = 10

[2] An assumption that growth will not be reduced until N content falls below 80% of demand

This description ensures that uptake by species *k* is:

1. proportional to its relative root length density L_{rv} if demand for all components is equal,
2. never more than the potential uptake by *i* in a monoculture with the same L_{rv},
3. not reduced if companion plants with a high root length density have zero demand (e.g. a tree just after pruning).

At this stage we apply this procedure to four species (n=4, i.e. 3 trees and a crop or weed in each zone), but the routine can be readily expanded to a larger number of plants interacting.

Root growth is represented for the crop by a logistic increase of root length density in each layer up till flowering time and gradual decline of roots after that time. A maximum root length density per layer is given as input. The model also incorporates a 'functional equilibrium' response in shoot/root allocation of growth, and a 'local response' to shift root growth to favourable zones. For the tree, root length density in all zones and layers can be assumed to be constant, thus a representing an established tree system with equilibrium of root growth and root decay or can follow dynamic rules roots similar to those for crop.

The **Soil Organic Matter** includes litter layer and organic matter. Both has three main pools (Active, Slow and Passive), following the terminology and concept of the CENTURY model.

Light capture is treated on the basis of the leaf area index (LAI) of all components and their relative heights, in each zone. Potential growth rates for conditions where water and nutrient supply are non-limiting are used as inputs (potentially derived from other models), and actual growth is determined by the minimum of shade, water and nutrient stress.

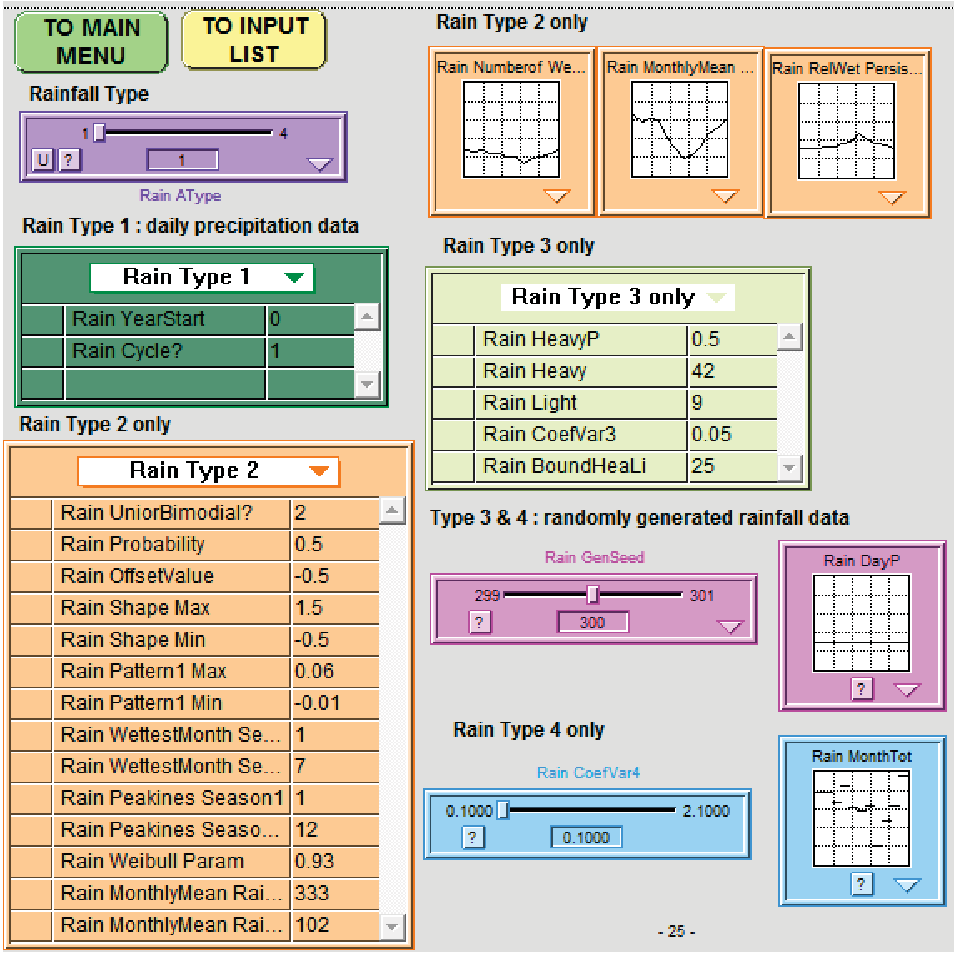
2.2. Model organization

STELLA allows the user three perspectives on a model:

1. On the upper layer, general information is provided, key parameters can be modified (Figure. 2.2A) and output can be obtained in the form of graphs and tables (Figure. 2.2B),
2. On the middle layer (Figure. 2.3A and Figure 2.3B), the model is presented as a complete compartment - flow diagram, with all equations entered at the respective 'converters'; double arrows indicate 'flows' from 'pools' in rectangles, while single lines indicate a flow of information; this is the working level for developing or modifying the model; a 1:1 relation is maintained between the diagram and the model relationships,
3. A listing of the model equations, with comments added.

At the middle level, the model can be arranged in sectors. To facilitate the process of finding parameters in the model, we made sure that all parameters in a sector start with letters referring to the sector. This way, an alphabetic listing of parameters as the **STELLA** shell does, gets functional significance. In chapter 3 we will start using the names of model parameters in WaNuLCAS. A selection of parameters (all those which are important as input values to be specified by the user) is given in Appendix 7.

In **STELLA** multiple representations of similar structures can be obtained by using arrays (indexed variables). In WaNuLCAS we use arrays for the 'zones' and in some cases, for the different soil layers. We also use arrays for nutrients (N and P) as they can be treated in parallel. Despite the symmetry in the uptake description between water and nitrogen, we found that there are enough differences to merit separate representation in the model, rather than a generic ‘belowground resources’. A number of parameters dependent on crop type are in an array called ‘crop’, and are utilized based on the crop sequence specified (see 3.1.4). To find out the various used in the model, see the array editor within the **STELLA** model.



Rain AType: 1 (range 1 – 4)

Rain Type 1

Rain YearStart	0
Rain Cycle?	1

Rain Type 2

Rain UniorBimodial?	2
Rain Probability	0.5
Rain OffsetValue	-0.5
Rain Shape Max	1.5
Rain Shape Min	-0.5
Rain Pattern1 Max	0.06
Rain Pattern1 Min	-0.01
Rain WettestMonth Se...	1
Rain WettestMonth Se...	7
Rain Peakines Season1	1
Rain Peakines Seaso...	12
Rain Weibull Param	0.93
Rain MonthlyMean Rai...	333
Rain MonthlyMean Rai...	102

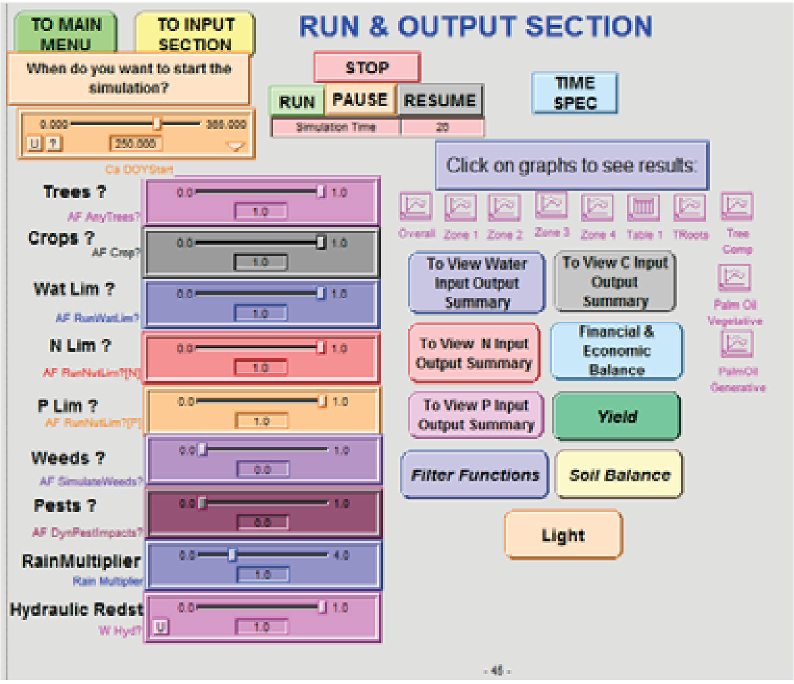
Rain Type 3 only

Rain HeavyP	0.5
Rain Heavy	42
Rain Light	9
Rain CoefVar3	0.05
Rain BoundHeaLi	25

Rain GenSeed: 300 (range 299 – 301)

Rain CoefVar4: 0.1000 (range 0.1000 – 2.1000)

Figure 2.2A. Upper level view on the WaNuLCAS model options for setting input values numerically or in graph (table) form; the buttons ‘to main menu’ and ‘to input list’ allow one to navigate through the input section.



When do you want to start the simulation?

Click on graphs to see results:

Figure 2.2B. Upper level view on the WaNuLCAS model with example of output graphs and tables.

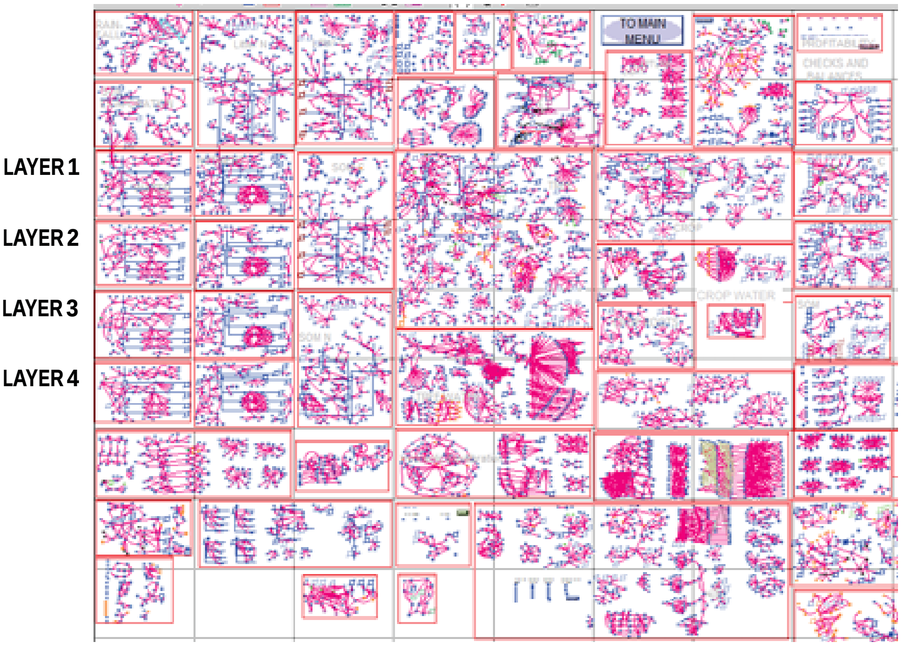


Figure 2.3A. A Middle level overview of the WaNuLCAS model in version 4.0.

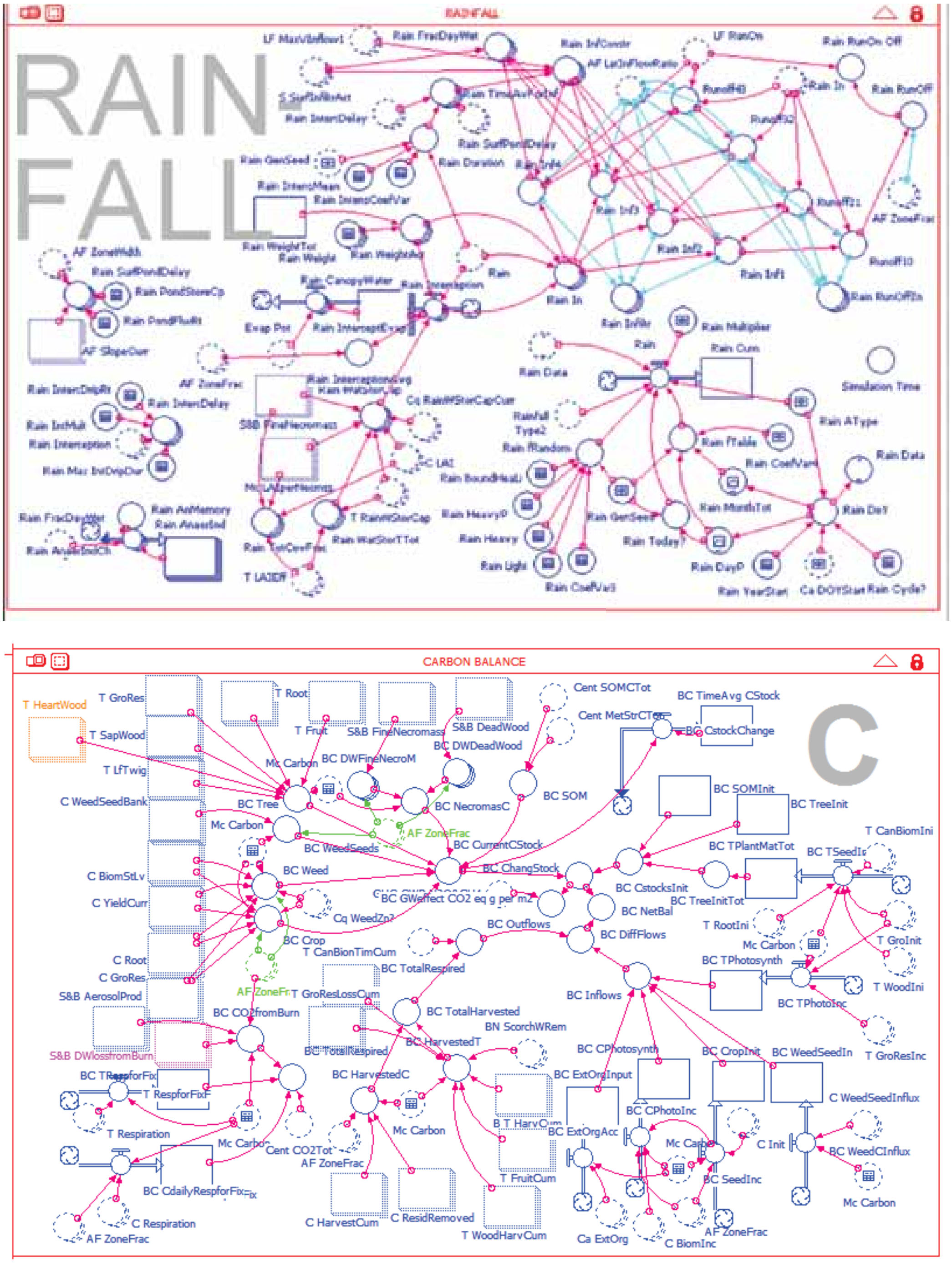


Figure 2.3B. Middle level view on the WaNuLCAS model with examples of 1 sectors.

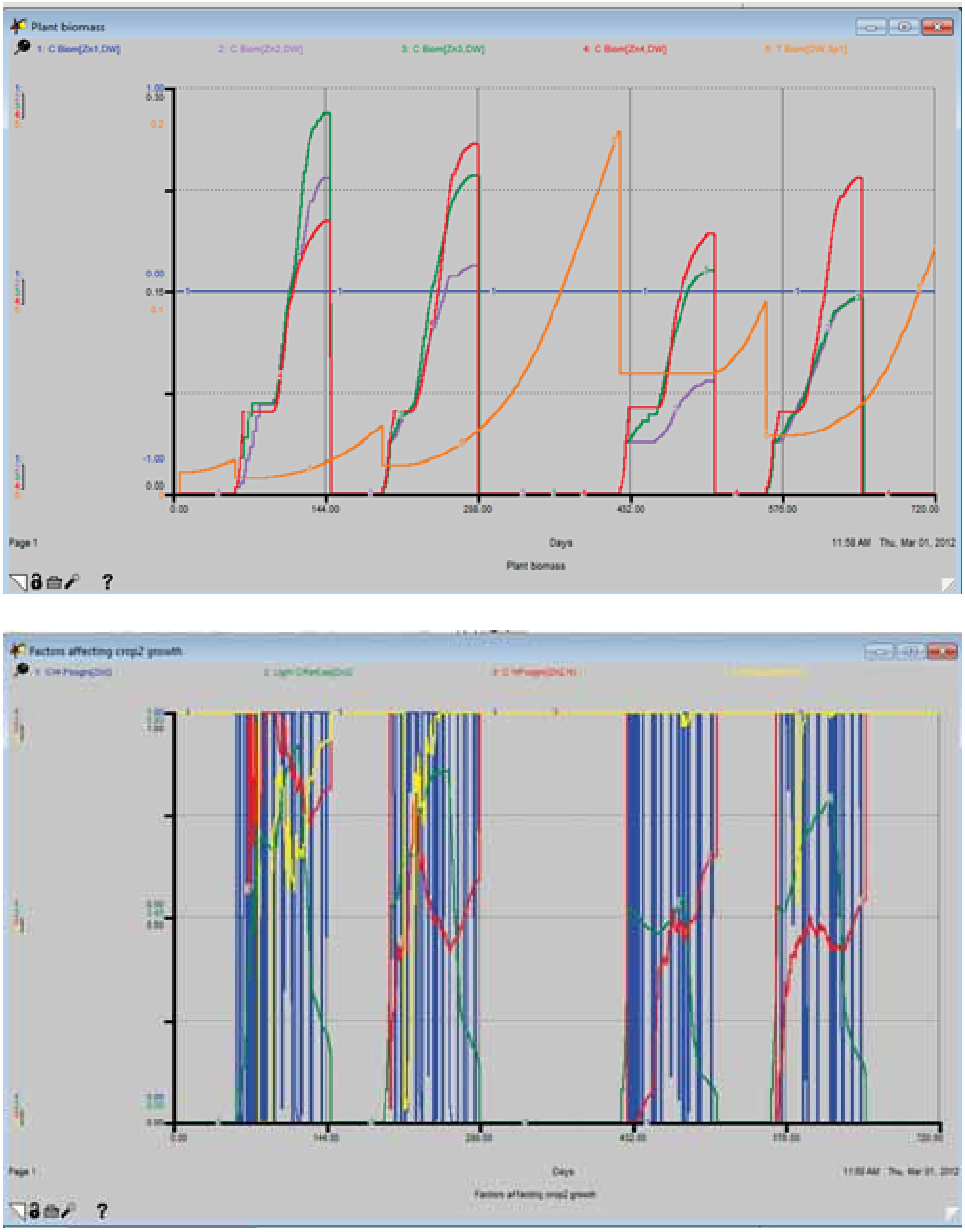


Figure 2.4. Example of output graphs.

Chapter 3

Description of Model Sectors

Confidence in the use of a model may be based on:

1. *accepting the main assumptions made as reasonable first approximations,*
2. *the use of reasonable parameter values, and/or*
3. *a proven ability of the model to predict measured outputs on the basis of appropriate input parameters.*

We will focus here on a description of the model structure chosen and its underlying assumptions.

Parameter names in WaNuLCAS always start with the first 1 or 2 letters of the sector in which they are placed. In this text, however, some of the parameter names are reduced to their core to make equations more readable. Please refer to Appendix 7 for the full list of parameter names.

3.1. Agroforestry systems

3.1.1. Zoning of the agroforestry system into four zones.

Normally, the first zone will be used for trees only. The other three zones will normally be used for growing crops, but they can be shaded by the trees in zone 1 (depending on canopy size and shape) and can harbour tree roots, leading to belowground competition (Figure 3.1. and Table 3.1). Normally the intensity of interactions will decrease from zone 2 to 4.

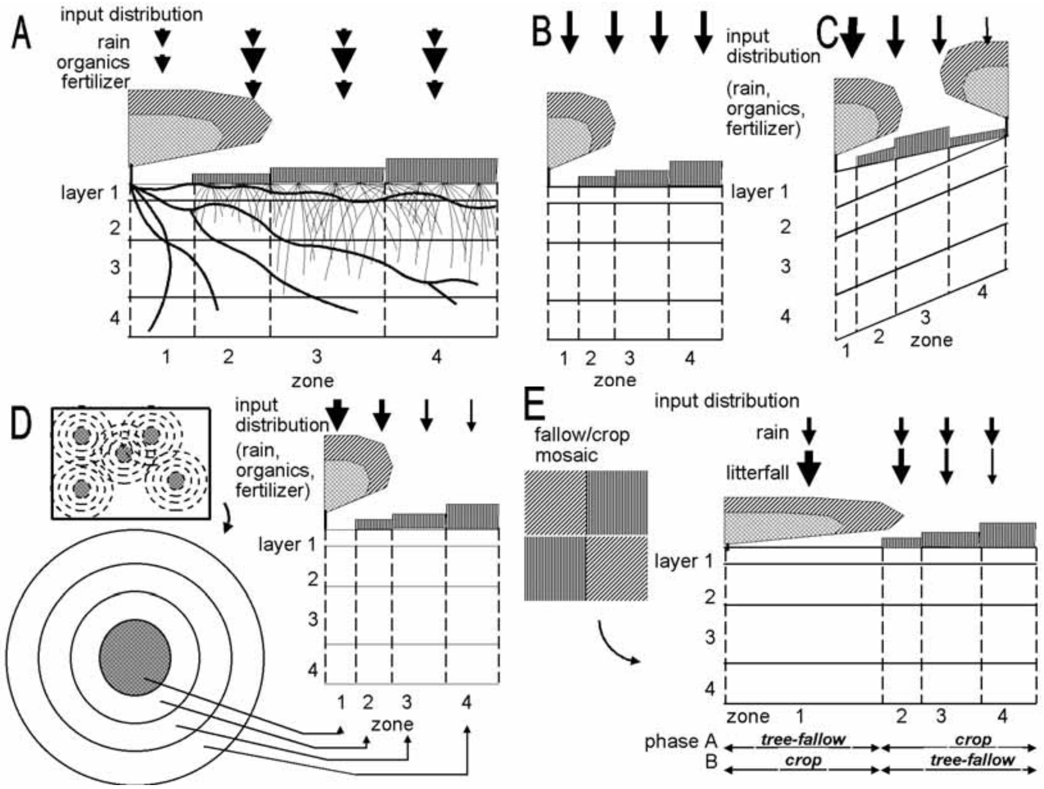


Figure 3.1. General lay out of zones and layers in the WaNuLCAS model (A) and applications to four types of agroforestry system: B. Alley cropping, C. Contour hedgerows on slopes, with variable topsoil depth, D. Parkland systems, with a circular geometry around individual trees, E. Fallow-crop mosaics with border effects.

In WaNuLCAS versions up to 3.2 two options were provided for tree locations: on the left (lower) side of Zone 1 or on the right (upper) side of Zone 4. The need for more flexible options arose when simulations were to be made for ‘double row’ systems as practiced for example in rubber, where the basic line of symmetry is in between tree rows.

Revising the algorithm for tree canopy development now allows for any position among the 4 zones to be used as the centre point of the tree crown, via two parameters: *AF_TreeZone[Tree]* indicates the zone in which each of the 3 allowable trees (of the same or different species) is located, *AF_TreeRelPos[Tree]* indicates the relative position [0-1] within this zone. *Note: aAdjustments to root distribution will (for now) have to be made manually.*

Table 3.1. Characteristic settings for nine types of agroforestry system.

	Geometry	Tree position, canopy	Topsoil depth	Water infiltration	Time sequence
Alley cropping on flat land	Linear, half alley + hedgerow	Zone 1, Zone 1 - 4	Homogeneous	Homogeneous, except for canopy interception	Continuous
Alley cropping on flat land, alternating hedgerow	Linear, alley + two hedgerows	Zone 1 + 4, Zone 1 - 4	Homogeneous	Homogeneous, except for canopy interception	Continuous
Alley cropping on slopes	Linear, alley + one hedgerow	Zone 1 + 4, symmetrical canopy	Gradient	Heterogeneous (-runoff + run-on)	Continuous (soil redis- tribution can be simulated)
Taungya transition into tree crops	Linear	Zone 1 + 4 Zone 1 - 4	Homogeneous	Homogeneous, except for canopy interception	Continuous
Agroforestation of *Imperata* grasslands	Linear, start with *Imperata* as 'crop'; half or whole alley	Zone 1 (+4), Zone 1 - 4	Homogeneous	Homogeneous, except for canopy interception	Continuous
Coffee+shade trees	Linear, use coffee as 'crop'	Zone 1 (+4), Zone 1 - 4	Homogeneous	Homogeneous, except for canopy interception	Continuous
Homegarden	Linear or Circle	Zone 1 (+4), Zone 1 - 4	Homogeneous	Homogeneous	Continuous
Parkland trees	Circle	Zone 1, Zone 1 - 4	Homogeneous	Heterogeneous	Continuous
Tree fallow/ mosaic	Linear	Zone 1, (fallow plot size)	Homogeneous	Homogeneous	Continuous or Switching between fallow and crop stage

Tests

Two tests were used in checking the algorithm: if all zones have equal width, the results for *Zone 1, RelPos 1* should be identical to those for *Zone 2, RelPos 0*, while the results for *Zone 1 or 2, RelPos X* should be a mirror image of those for for *Zone 4 or 3, RelPos (1-x)*. The current algorithm passed both tests.

Basic concept

The canopy can expand both towards the right and towards the left of the tree position and will 'spill over' into the next zone to the left or right when it reaches the zone boun¬dary. As indicated by the arrow in Figure 3.2, when the tree is not in the middle of the zone, it will reach one boundary before the other, and the rate of increase of RelCanWidth[Zone] will be half of what it was before at the time the next zone starts to fill.

Example of results

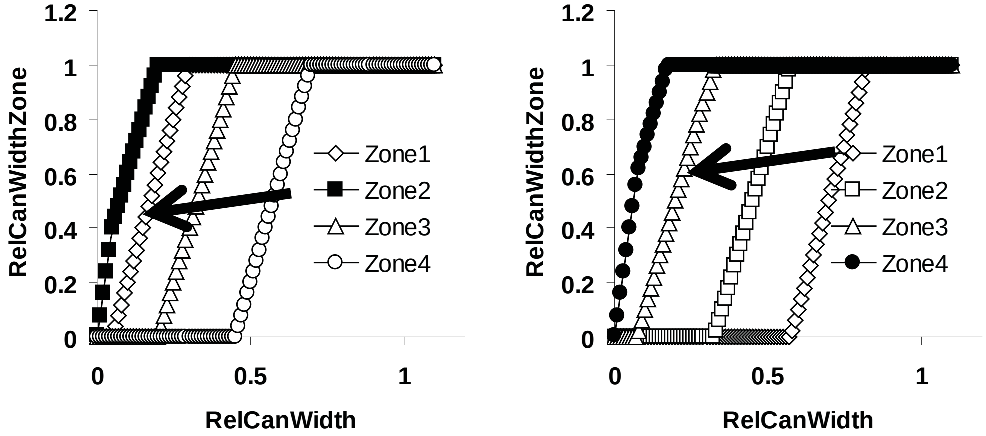


Figure 3.2. Examples of the relationship between RelCanWidth for the whole simulation area and RelCanWidthZone[Zone]; A. The tree is positioned in Zone 2 at RelPos 0.2 ; B The tree is in Zone 4 at RelPos 0.3; arrow explained in the text

Technical implementation

TreeCanWidthZone[Zone] = IF AFZone[Zone] = 0 then 0 Else IF (TreeInZone?[Zone] = 1 then MIN(1,(MAX(0,MIN(RelPos* AfZone[Zone],RelCanWidth))+MAX(0,MIN((1-RelPos)* AfZone[Zone], RelCanWidth)))/ AfZone[Zone]), Else MAX(0,MIN(1,(RelCanWidth – (Tree1ToTheLeft?[Zone] * RelAFZoneTreeLeft[Zone] + Tree2ToTheLeft?[Zone] * RelAFZoneNextLeft [Zone] + Tree3ToTheLeft?[Zone] * RelAFZoneNxt2Left[Zone] + Tree1ToTheRight?[Zone] * RelAFZoneTreeRight[Zone] + Tree2ToTheRight?[Zone] * RelAFZoneNxtRight[Zone] + Tree3ToTheRight?[Zone] * RelAFZoneNext2Right[Zone]))/ AfZone[Zone]))))
With a number of auxiliary variables:
TreeInZone?[Zone] = IF AF_TreeZone = ZoneNumber[Zone] Then 1 Else 0
Tree1ToTheLeft?[Zone] = IF AF_TreeZone < ZoneNumber[Zone] Then 1 Else 0
Tree2ToTheLeft?[Zone] = IF AF_TreeZone < ZoneNumber[Zone]-1 Then 1 Else 0
Tree3ToTheLeft?[Zone] = IF AF_TreeZone < ZoneNumber[Zone]-2 Then 1 Else 0
Tree1ToTheRight?[Zone] = IF AF_TreeZone > ZoneNumber[Zone], Then 1 Else 0
Tree2ToTheRight?[Zone] = IF AF_TreeZone > ZoneNumber[Zone]+1, Then 1 Else 0
Tree3ToTheRight?[Zone] = IF AF_TreeZone > ZoneNumber[Zone]+2 Then 1 Else 0
RelAFZoneTreeLeft[Zone] = (1-RelPos)* (IF TreeZone=1 Then AFZoneWidth[1] Else If TreeZone=2 then AFZoneWidth[2] else if TreeZone=3 then AFZoneWidth[3] else if TreeZone=4 then AFZoneWidth[4] else 0)
RelAFZoneNextLeft[Zone] = IF TreeZone =1-1 then AFZoneWidth[1] else IF TreeZone =2-1 then AFZoneWidth[2] else IF TreeZone =3-1 then AFZoneWidth[3] else IF TreeZone =4-1 then AFZoneWidth[4] else 0

RelAFZoneNext2Left[Zone] = IF TreeZone =1-2 then AFZoneWidth[1] else IF TreeZone =2-2 then AFZoneWidth[2] else IF TreeZone =3-2 then AFZoneWidth[3] else IF TreeZone =4-2 then AFZoneWidth[4] else 0

RelAFZoneTreeRight[Zone] = RelPos* (IF TreeZone=1 Then AFZoneWidth[1] Else If TreeZone=2 then AFZoneWidth[2] else if TreeZone=3 then AFZoneWidth[3] else if TreeZone=4 then AFZoneWidth[4] else 0)

RelAFZoneNextRight[Zone] = IF TreeZone =1+1 then AFZoneWidth[1] else IF TreeZone =2+1 then AFZoneWidth[2] else IF TreeZone =3+1 then AFZoneWidth[3] else IF TreeZone =4+1 then AFZoneWidth[4] else 0

RelAFZoneNext2Right[Zone] = IF TreeZone =1+2 then AFZoneWidth[1] else IF TreeZone =2+2 then AFZoneWidth[2] else IF TreeZone =3+2 then AFZoneWidth[3] else IF TreeZone =4+2 then AFZoneWidth[4] else 0

Where topsoil depth is varied between zones one should observe constraints so that average topsoil depth over the slope remains realistic (compare 3.2.7).

The model calculates mass balances for a basic unit of area (say 1 m^2) in each zone or as (weighted) average for the whole system simulated. A weighted average is used, for example for expressing total yields of the system on an area basis, when accounting for tree roots and their uptake from the various zones. The relative weights are AF_ZoneFrac[Zn*i*] and are calculated such that they add up to 1.0.

The four AF_ZoneFrac[Zone] values are calculated from the following four input values: AF_Zone[Zn1], AF_Zone[Zn2], AF_Zone[Zn3] and AF_Zonetot. AF_Zone[Zn4] is calculated by difference.

For example: *AFZoneFrac[Zn1] =(AF_Zone[Zn1])/(AF_ZoneTot)* **[4]**

If a circular geometry is used (AF_Circ = 1), the AF_ZoneFrac[Zone] values are derived from the AF_Zone[Zone] differently (on the basis of circle rings, $(r_i^2 - r_{i-1}^2)/ r_4^2$), but otherwise the model can run in the same way. The user has to specify four depths (thickness) of layers under the parameter name AF_DepthLay*i*. The layers will be homogeneous for four zones in each layers.

3.1.2. Input weighting factors

A number of inputs to the soil surface can be distributed homogeneously (proportional to the respective AF_ZoneFrac values), or heterogeneously. This way, we can for example account for. The model expects four input values 'Rain_Weight[Zn*i*]' and calculates effective weights from:

$$RainWeightAct[Zn_i] = \frac{RainWeight[Zn_1]}{\sum_1^4 AFZoneFrac[Zn_i]xRainWeight[Zn_i]} \qquad \textbf{[5]}$$

This equation ensures that the average rainfall remains at the value specified; the units for the RainWeightAct parameters are arbitrary. Multiplied with the rainfall per unit area (overall average), we then obtain the rainfall per unit area in each zone *i*. Similar weighting factors are used in T_LitfallWeight, T_PrunWeight for allocating tree litterfall and tree prunings over the various zones, while conserving their overall mass balance. The units for these weighting factors are arbitrary, as they are only used in a relative sense.

3.1.3. Calendar of events

The year in WaNuLCAS starts with Year 0, while the day is value from 1 to 365. Starting day of the simulation can be specified at any time after DOY 1 of Year 0.

Before a simulation, the user can specify a number of events that will take place at a given calendar date usually by specifying the Year and Day-of-Year (DOY) in which they will occur. Some events will be triggered internally, such as crop harvest when a crop is ready for it or a burn event after the slash has dried sufficiently. It may help the model user to design such a calendar. Figure 3.3 and Table 3.2 give an example of calendar of events for a hedgerow systems with Gliricidia as tree and maize - groundnut as crops. To help users in defining Julian days, we provide a list of Julian days in Wanulcas.xls – sheet 'Julian Days'.

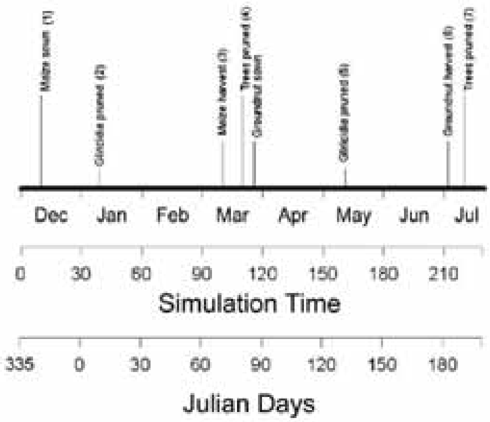


Figure 3.3. A schematic diagram of management activities of a hedgerow systems.

Table 3.2. An example of management activities record of a hedgerow systems.

No.	Activities	Date	Year in WaNuLCAS	Day in WaNuLCAS
1.	Planting maize	11 December 1994	0	345
2.	Pruning Gliricidia	8 January 1995	1	8
3.	Maize harvest	10 March 1995	1	69
4.	Pruning Gliricidia	20 March 1995	1	79
5.	Planting groundnut	27 March 1995	1	86
6.	Pruning gliricidia	14 June 1995	1	165
7.	Groundnut harvest	2 August 1995	1	214
8.	Pruning Gliricidia	7 August 1995	1	219

3.1.4. Crops, weeds and trees

The model user can schedule a sequence of crops (of different types) to be grown at one time for each zone, with specific fertilizer applications. For each simulation five crop types can be pre-selected from the database in the Wanulcas.xls spreadsheet. The crop type to be planted, in a given year and day (within year) can be specified for each zone by modifying the graphs Ca_CType, Ca_PlantYear and Ca_PlantDoY. Similarly, subsequent fertilizer applications are specified by the graphs Ca_FertOrExtOrgAmount, Ca_FertOrExtOrgAppYear, Ca_FertOrExtOrgAppDoY, Ca_FertApply?, Ca_OrExtOrgApply?.

There is no limit to the number of crops or fertilizer applications specified this way, as the x-axis of the graphs can be extended. A sequencing routine makes sure that crops which have been planted keep priority and new crops can only start after the current one has been harvested (as specified by the duration of its vegetative and generative phases set for the crop type). If a new crop should have been planted before the previous one is harvested, it is skipped from the sequence and the model will wait for the first new planting data specified.

Each crop has a maximum dry matter production rate per day, expressed in kg m^{-2} day^{-1}, Cq_GroMax and a graphic input of Cq_RelLUE[cr*i*] giving the relative light use efficiency as a function of crop stage. These parameters may be derived for a given location from more specific models, such as the DSSAT family of crop growth models or WOFOST (see section 3.7 for further details).

Annual or perennial weeds can be simulated using the ‘infrastructure’ of the crop model, and a seed bank that allows weeds to regenerate whenever there is no crop cover is included. At the moment, however, no crop-weed interaction within a zone can be simulated (see 3.10.4).

Trees can be planted, pruned and harvested at set calendar dates, using either of the three copies of ‘tree’ available. Allometric equations, which can be derived from fractal branching rules in a separate spreadsheet, govern the allocation of growth resources over the various tree organs. Trees can be pruned in the model to a specified degree on the basis of a user-specified set of dates (T_PrunY and T_PrunDoY, similar to the crop sequence), or on the basis of one or two criteria: concurrence with a crop on the field and when the tree biomass exceeds a ‘prune limit’ (see section 3.10.7 for details). Prunings can be returned to the soil as organic input or (partially) removed from the field as fodder.

3.1.5. Animals and soil biota

The model does not at this stage include a livestock component, but it can be used to predict fodder production and the tree pruning rules can be used to describe fodder harvesting or grazing. In such a case external inputs of manure may have to be included. Soil biota are implicitly accounted for in the parameters of the decomposition model, in the parameters describing the degree of mixing of organic inputs between surface litter and the various soil layers, in the creation of soil macropores (influencing bypass flow) and in N fixation or P mobilization.

3.2. Soil and climate input data

3.2.1. Soil physical properties

For calculating water infiltration to the soil, a layer-specific estimate of the 'field capacity' (soil water content one day after heavy rain) is needed. For calculating potential water uptake a table of the soil's 'matric flux potential' is needed, which integrates unsaturated hydraulic conductivity over soil water content. The model also needs the relationship between water potential and soil water content, to derive the soil water content equivalent to a certain root water potential. As these relationships are not generally measured for all soils where we may want to apply the WaNuLCAS model, 'pedotransfer' functions (Arah and Hodnett, 1997) are used. We derive parameters of the Van Genuchten equations of soil physical properties via a 'pedotransfer' function from soil texture, bulk density and soil organic matter content. The function selected was developed by Wösten *et al*. (1995, 1998). As this pedotransfer function is based on soils from temperate regions, one should be aware of its possible poor performance on soils with a low silt content, as the combination of clay + sand at low silt contents is much more common in the tropics than in temperate regions.

In WaNuLCAS versions up to 3.1 Van Genuchten equation developed by Woesten *et al*., (1995, 1998) is the only option to generate soil hydraulic properties. Van Genuchten equation was developed based on temperate soils. By adding new algorithm (Tomasella and Hodnett, 2002), now WaNuLCAS more adaptable to generate soil hydraulic properties for tropical soils.

The pedotransfer function is included in the Excel file Wanulcas.xls and after the user has specified clay, silt and organic matter content and bulk density of the soil, all the tables are generated which WaNuLCAS needs. The user then has to copy these tables to the sheets representing each zone, replicating them for each layer. This way different soil physical parameters can be used for any layer and zone in the model. Further instructions are given in the spreadsheet itself.

Soil texture	=>	Van Genuchten	=>	Tabulated	=>	Soil by layer
Soil organic matter		parameters		water retention,		in WaNuLCAS.STM
Soil bulk density				matric flux potential		

Suprayogo (2003) produced a pedotransfer database for tropical soils containing 8915 data available worldwide. The data were then used to asses the performance of the pedotransfer function used in WaNuLCAS model in predicting soil physical relationships (θ-h-K). The results appeared close to the field measurement. The largest deviations occured on vertisols and mollisols, where bulk density and soil organic matter content diverged.

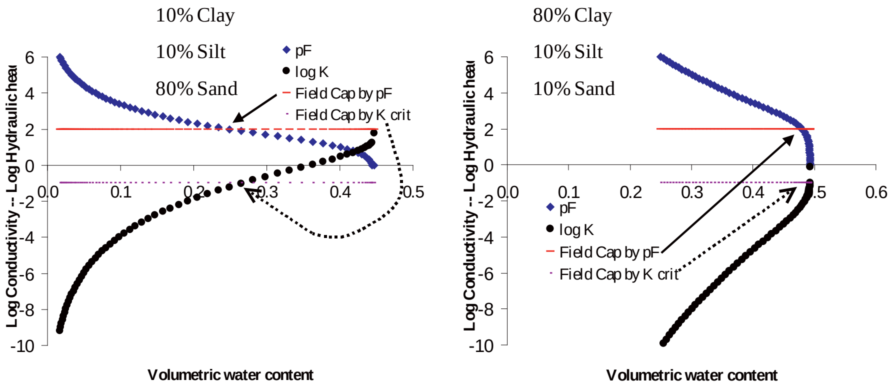


Figure 3.4. Relations between soil water content (X-axis), hydraulic head (expressed as pF or -log(head) -- positive Y axis) and unsaturated hydraulic conductivity (negative Y axis) for a dandy (left) and a clayey (right) soil, based on the pedotransfer function used in Wanulcas.xls; two definitions of 'field capacity' are indicated: one based on a user-defined limiting hydraulic conductivity, and one based on a depth above a groundwater table, defining a pF value; in the model the highest value of the two for each layer and zone will be used to determine maximum soil water content after a heavy rain event.

3.2.2. Temperature

Soil Temperature data are used to modify soil organic matter transformations. They can be entered as:
A. [Temp_AType = 1] a constant (Temp_Cons) ,
B. [Temp_AType = 2] as a table with monthly average values (Temp_MonthAvg), or
C. [Temp_AType = 3] as a daily values (Temp_DailyDat) linked to a sheet 'Temperature' in the Wanulcas.xls spreadsheet

Air temperature data through C_Topt and C_Tmin parameters are used to modified the length of cropping season. Current default values for air temperature ensure the length of cropping season = Cq_TimeVeg + Cq_TimeGen as specified on Wanulcas.xls.

3.2.3. Potential evapotranspiration

There are 2 options for the potential evapotranspiration rate: for Temp_EvapPotConst? = 1 a constant value is used throughout the simulation (Temp_EvapPotConst), while Temp_EvapPotConst? = 0 a daily value (Temp_EvapPotDailyData) is read from the excel spreadsheet. This can be calculated, for example from a (modified) Penman-Monteith equation or thornthwaite equation on the basis of climatological data for the site.

In this version 4.0, WaNuLCAS has elaborated estimation of daily potential evapotranspiration based on thornthwaite equation with air temperature and day length as its main inputs.

The potential rate of evapotranspiration is used to drive evaporation from canopy interception water (whenever present), trees and crops (but limited by plant water stress if present), dead wood piles on the soil after a slash event and finally by the soil (if any demand is unsatisfied as yet).

3.2.4. Rainfall

Rainfall data can be either generated within WaNuLCAS, or be obtained from an Excel spreadsheet. Setting the 'Rain_AType' parameter makes the choice:
1 = Tabulated daily rainfall records from an external file.
2 = Random generator based on monthly data using rainfall simulator
3 = Random generator based on heavy and light rainfall data
4 = Monthly average tabulated data (with given probability of daily rainfall and normal random variation around the average values).
The four options are summarized in Table 3.3.

Table 3.3. Three options for deriving daily rainfall values.

Rain_AType	1 = Tabulated daily rainfall	2 = rainfall simulator	3 = Random generator	4 = Variation around monthly total
Probability of rain on a given day	not applicable	Probability for four rainfall occurrences (D|D, D|W, W|W, W|D)	Rain_DayP, split via Rain_HeavyP into 'light' (0.5-25) and 'heavy' (> 25 mm/day) rains	Rain_DayP
Amount of rain	Read from table	Probability distribution functions based on single- and multi-parameter models.	Normal distribution around Rain_Light and Rain_Heavy (truncated at zero)	Normal distribution around Rain_MonthTot / (Rain_DayP * 30) (truncated at zero)
Variability of rainfall	Implicit in data read from table		Rain_CoeffVar for heavy rain category, for light rain a standard deviation of 5 is used	Rain_CoeffVar

For choice 1, the data should be copied to sheet 'rainfall' to column 3 of a spreadsheet with name Wanulcas.xls. This spreadsheet has in column 1 real dates (optional), in column 2 days {1... end} and in column 3 {rainfall in mm/day}. Alternatively, a new **STELLA** link can be established between the 'Rain data' table in WaNuLCAS and another relevant spreadsheet. Missing data should be addressed outside of WaNuLCAS.

If the user would like to use a different rainfall generator, the easiest way would be to generate rainfall data outside of WaNuLCAS copy the results to the Wanulcas.xls spreadsheet and set Rain_AType to 1.

For choise 2, number of parameters (Appendix 7) is needed to run this rainfall type. A help file to generate these parameters is available in excel file. This rainfall type generating daily rainfall data based on common 'Markov chain' way, which basically consists of two steps: i) simulating rainfall occurrence, i.e. determining whether or not a day is a rainy day or not, and ii) for rainy days, determine the amount of rainfall (Appendix 10).

For choice 3, six parameters are needed: the probability of rainfall on a given day RainPday), the probability that rainfall is of type ‘heavy’ rather than ‘light’ (Rain_HeavyP), the boundary value of heavy and lighrt rains (Rain_BounHeaLi), the average value of ‘light’ and ‘heavy’ rains (Rain_Light and Rain_Heavy) and a coefficient of variability for heavy rain (Rain_CoefVar). Light rain is truncated from a normal distribution with 0.5 as minimum and Rain_BoundHeaLi (default 25 mm) as maximum value, heavy rain is truncated with Rain_BoundHeaLi as minimum. The standard deviation for light rains is as a standard input at 5 mm (but can be modified inside the equation for **STELLA** users).

For choice 4, tabulated monthly averages are entered in ‘Rain_MonthlyTot’. Daily rainfall is derived from a normal distribution around this average value, with a standard deviation defined as coefficient of variation.

$$Rain = max(0, Rain\_Today)xNormal\left(\frac{Rain\_MonthTot}{30xRain\_DayP}, \frac{Rain\_CoefVarxRain\_MonthTot}{30xRain\_DayP}, RainSeed\right) \quad \textbf{[6]}$$

The ‘Normal’ function in **STELLA** has three arguments: mean, standard deviation and seed. We protect against negative rainfall values for obvious reasons.

The linked data for option 1 and tabulated monthly data in option 4 may start at any ‘day of year’ before the simulation starts. They are read via Day of Year’ variable Rain_DOY = Mod(Time + Cq_DOYstart, 365). For option 1 one can start at any year of the climatic data set by specifying Cq_YearStart (one should be careful not to have the simulation start before or extend beyond the rainfall data set in such a case. It is possible to repeatedly use the rainfall data for a single year for a multiyear run (RainCycle? = 1), or to read multi-year data from the Excel spreadsheet run (RainCycle? = 0). One would normally start reading rainfall data at year 0; if one wants to start at a later point in the data set, the parameter Cq_YearStart has to be adjusted. The Rain_DayP values are given as a monthly tabulated function of Day of year.

3.2.5. Canopy interception of rainfall

Part of any rainfall event will not reach the soil surface because the tree or crop canopy intercepts it. This interception process has been included on the basis of a maximum water storage capacity of the tree + crop canopy, calculated as a thickness of water film times the leaf area index (ignoring water stored on stem surfaces). Water will evaporate from this intercepted layer at a speed equal to the potential evapotranspiration rate, with priority over crop and tree transpiration or soil evaporation.

3.2.6. Soil redistribution on slopes

Soil particles can get detached during rainfall events, move along with surface runoff water and may get entrenched or filtered out where the waterflow slows down on a rough surface or encounters a zone of high net infiltration rates. Soil particles can also be moved by soil tillage (section 3.10.8), especially by ploughing. The amount of soil particles leaving the border of any measurement area is a balance of the amount entering it from above, plus the amount of soil starting to move within the area, minus the amount filtered. A process level description of such events should consider a time scale of minutes (or less) and deal with considerable heterogeneity in conditions at the soil surface. For WaNuLCAS we've chosen for a more aggregated description, in line with the daily time step, but maintain:

$$Soil\_outflow = (1 - filterefficiency)x(soil\_inflow + soil\_stirredup) \qquad [7]$$

where the filter efficiency is expressed as fraction of the soil moving. For a typical situation with contour hedgerows (or other vegetative filter strips), we can allocate most of the filter effect to 'Zone 1', while soil cover in all zones modifies the amount of soil stirred up.

A further simplification, although not strictly necessary for the model to function, is to assume that at any time the soil surface is approximately a plane within the zones considered. The main issues then are:

1. how does the soil slope change over time,
2. how much is the net outflow from one simulated land unit,
3. how are the properties of the topsoil modified in each zone due to the soil movement and filter effects.

Change of slope

We want to derive the terrace height hx and the final slope (h'/w) from the initial_slope (h/w), the amount of soil moved and the amount lost. We first assume that the position of point A is fixed and that soil accumulation (terrace formation) can increase the level to point A' but not decrease the level. From Fig. 3.5 we can see that:

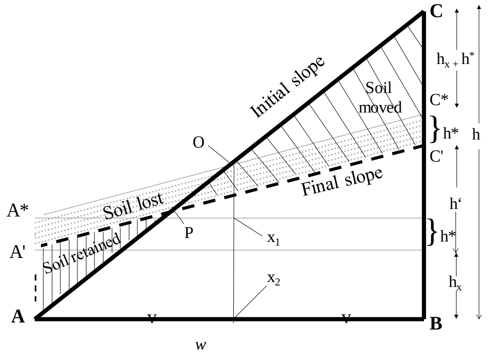


Figure 3.5. Terminology for describing change of slope: ignoring the soil below the boundary A-B which will not be affected by the changes and assuming that the bulk density of the soil is constant, the redistribution process modifies the triangle A-B-C (with a width w, a height h and a slope-length s) into the polygon A-A' -C'-B (with height h' and slope length s'), plus the soil loss which is proportional to A'A*C*C', or wh*; the triangle AA*O is equal to OCC*

$$h = 2(h_x + h^*) + h' \qquad [8]$$

$$\frac{Soil\_lost}{bulkdensb} = ABC - AA'C'B = A'A^*C^*C' = h^*w \qquad [9]$$

$$\frac{soilretained}{bulkdensb} = \frac{(Soil\_moved - Soil\_lost)}{bulkdensb} = AA'P = \left(\frac{h}{(h_x+h^*)}\right) AA^*O = \left(\frac{h}{(h_x+h^*)}\right)(AA^*X_1X_2 + A^*OX_1 - AOX_2) = \left(\frac{h}{(h_x+h^*)}\right)\left(\frac{(h-h')w}{4} + \frac{h'w}{8} - \frac{hw}{8}\right) = \frac{\left(\frac{h_x}{(h_x+h^*)}\right)w(h-h')}{8} = \frac{wh_x}{4} \qquad [10]$$

Hence,

$$Terrace\_height = h_x = \frac{4(Soil\_moved - Soil\_lost)}{(bulkdensbw)} \qquad \textbf{[11]}$$

If Soil_lost = Soil_moved and thus Soil_retained = 0, this leads to hx = 0.
Combining [*x4], [*x3], [*x2] and [*x1] we obtain:

$$Final\_slope = Initial\_slope - \frac{(8Soil\_moved - 6Soil\_lost)}{(Bulkdensbw^2)} \qquad \textbf{[12]}$$

If Soil_moved and Soil_lost are expressed in Mg, w in m, the model is applied to a breadth b of 1 m and bulkdensity in Mg m^{-3}, the final slope in indeed dimensionless.
For the time being the effect of soil movement on the soil quality of the receiving zones (soil C, N and P contents, soil physical properties) are ignored, i.e. we assume the incoming soil to have the same properties as the average of the receiving zone. This may cause inconsistencies in the total C, N and P balance and will need further attention in a future release.

The situation where point A is not fixed, can lead (in the absence of filter functions) to a parallel decline of topsoil height, without change in slope angle.

3.2.7. Soil erosion

Soil erosion module applies to sloping land situation only. WaNuLCAS uses ROSE (physical equation) equations to estimate soil erosion. Tillage will affect soil erosion (see 3.10.8)

3.3. Water balance

3.3.1. Soil water storage infiltration and evaporation

For the description of the soil water balance in soil-plant models a number of processes should be combined which act on different time scales (Figure 3.6):

1. rainfall or irrigation (with additional run-on) and its allocation to infiltration and surface run-off (and/or ponding), on a seconds-to-minutes time scale,
2. infiltration into and drainage from the soil via a cascade of soil layers, and/or via ‘bypass’ flow, on a minutes-to-hours time scale,
3. subsequent drainage and gradual approach to hydrostatic equilibrium on a hour-to-days time scale,
4. transfers of solutes between soil layers with mass flow,
5. evaporation from surface soil layers on a hour-to-day time scale,
6. water uptake on a hour-to-days time scale, but mostly during daytime when stomata are open,
7. hydrostatic equilibration via root systems on a hour-to-days time scale, but mostly at night when plant transpiration is negligible,
8. hormonal controls (‘drought signals’) of transpiration on a hour-to-weeks time scale,
9. changes in macropore volume (and connectivity) based on swelling and shrinking of soils closing and opening cracks, and on creation and destruction of macropores by soil macrofauna and roots; this acts on a day-to-weeks time scale. Its main effect will be on bypass flow of water and retardation of nutrient leaching.

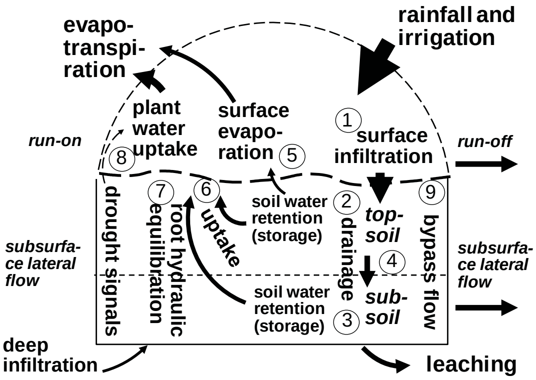


Figure 3.6. Elements of the water balance included in the WaNuLCAS model: 1. surface infiltration of rainfall, 2-4. Redistribution of water and solutes over the profile, recharging soil water content (2) and draining (leaching) excess water from the bottom of the profile, 5. surface evaporation, 6. water uptake by tree and crop roots, 7. hydraulic equilibration via tree roots, 8. drought signals influencing shoot:root allocation and 9. bypass flow of solutes.

The WaNuLCAS model currently incorporates point 1...7 and 9 of this list, but aggregates them to a daily time step; drainage to lower layers is effectuated on the same day as a rainfall event occurred. An empirical infiltration fraction (as a function of rainfall intensity, slope and soil water deficit) can be implemented at patch scale. Between the zones of the WaNuLCAS model, surface run-off and run-on resulting in redistribution among zones can be simulated on the basis of a user-specified weighing function for effective rainfall in the in the various zones.

Table 3.4. Water balance at patch level in WaNuLCAS

In	Out
Initial soil water content for all zones and layers	Final soil water content for all zones and layers
Patch-level run on	Patch-level run-off
Lateral inflow	Drainage from bottom of soil profile and lateral outflow
Rainfall	Soil evaporation
Irrigation (added as extra rainfall)	Evaporation of intercepted water
	Transpiration by tree
	Transpiration by crop
	Transpiration by weed

Upon infiltration a ‘tipping bucket’ model is followed for wetting subsequent layers of soil, filling a cascade of soil layers up till their effective ‘field capacity’. Field capacity is estimated from the water retention curve (see section SOIL above). In WaNuLCAS, S_SeepScalar is an additional parameter (a constant value range 0 - 1) that also control the amount of water that infiltrate to the deeper soil layer.

Soil evaporation depends on ground cover (based on LAI of trees and crops) and soil water content of the topsoil; soil evaporation now stops when the top soil layer reaches a water potential of -16 000 cm.

A simple representation of by-pass flow is added, but only in its effects on nutrient leaching (see 3.4.3). Dynamics of macropore are described in section 3.3.7.

3.3.2. Water uptake

Water uptake by the plants is driven by their transpirational demand, within the possibilities determined by roots length density and soil water content in the various cells to which a plant has access.

The calculation procedure used by De Willigen and Van Noordwijk (1987, 1991) is based on an iterative procedure, solving the simultaneous equations for soil + plant resistance as a function of flow rate, and of flow rate as a function of the resistance's involved. As this routine can not be implemented as such in a **STELLA** environment, we chose for an approximate procedure, where some of the feed-back is included on an a-priori basis, and an other part is implemented in the next time step, by keeping track of the plant water status inherited from the previous day.

Plant water potential is calculated on the basis of soil water potential (weighted average over all zones and layers on the basis of local root length density, minus the potential to overcome root entry resistance if full transpirational demand is to be met, and a term to cater for expected soil resistance (estimated as 10% of soil water potential; a more precise value is calculated in step 5 of the daily procedure – see below)).
The sequence of events in modeling water uptake (Figure. 3.7), more detail equations are presented in Appendix 5 and 11:

1. Estimate potential transpirational demand E_p from potential dry matter production (an input to WaNuLCAS, derived from other models), diminished to account for the current shading and LAI, multiplied with a water use efficiency (CW_TranspRatio, again a model input, reflecting climate and crop type),
2. Estimate plant water potential on the basis of the various resistances in the catenary process:
   (a) soil water potential as perceived by the plant (weighted average over all zones and layers on the basis of local root length density),
   (b) a term to cater for expected resistance between bulk soil in the voxel and the root surfaces (in the default situation initially estimated as 5% of soil water potential; a more precise value is calculated in step 5 of the daily procedure – see below)
   (c) the potential gradient needed to overcome root entry resistance if full transpirational demand is to be met
   (d) the potential gradient needed to overcome root axial transport resistance if full transpirational demand is to be met.
3. On the basis of this plant water potential, calculate the transpiration reduction factor f_p on the basis of a function proposed by Campbell (De Willigen *et al.*, 2000),
4. Use the reduced uptake demand f_p E_p to estimate the rhizosphere potential h_{rh} for all voxels i from the plant potential h_p minus the potential gradient needed to overcome the axial transport distance given the length of the pathway from voxel to stem base (Radersma and Ong, 2004),
5. Calculate potential water uptake rates for all layers i on the basis of $h_{s,i}$ and h_{rh} and their equivalent matric flux potentials F; the matrix flux potential is the integral over the unsaturated hydraulic conductivity and can be used to predict the maximum flow rates which can be maintained through a soil (De Willigen and Van Noordwijk, 1994), taking into account that the drier the soil the more difficult it is to move water through a reduced water-filled pore space

6. Calculate real uptake as the minimum of demand (f_p*E_p) and total supply (summed over all layers i) and allocate it to layers on the basis of potential uptake rates,
7. Recalculate soil water contents in all layers i for the next time step.
8. Calculate a 'water stress factor' from real uptake as fraction of potential transpirational demand; real growth is based on the minimum of the 'water stress' and 'nutrient stress' factor and potential growth.

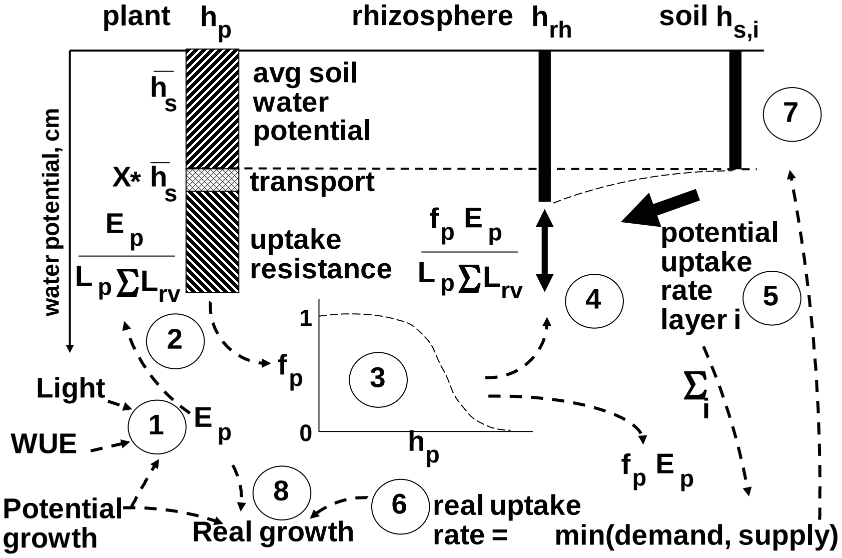


Figure 3.7. Steps (1…8) in daily cycle of calculations of water uptake; the interrupted arrows represent information flows.

The procedure for water uptake is similar to that for nutrient uptake (see below), but the transport equations are analogous in terms of 'matric flux potential' rather than soil water content. A further complication for allocating water uptake is that plant water potential may differ between roots of the various components in a given cell. In the model the highest (least negative) is used first to share out potential water uptake to all components, followed by additional uptake potential for components with a lower water potential (Figure 3.8).

The model in its current form does not include 'drought signals'. It may be possible to represent such direct effects of root-produced hormones on stomatal closure by adding a relation between CW_PotSoil (the averaged water potential around the roots of a crop) and the CW_DemandRedFac, beyond their current indirect relation via CW_PotSuctCurr.

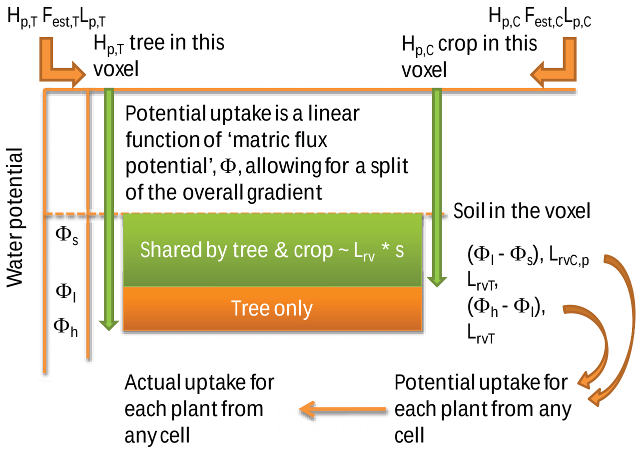


Figure 3.8. Diagram of sharing out available water by tree and crop.

3.3.3. Hydraulic lift and sink

An option exist to simulate hydraulic lift and hydraulic sink phenomena in tree roots, transferring water from relatively wet to relatively dry layers. The parameter W_Hyd? determines whether or not this is included (0 = not, 1 = yes). Hydraulic continuity via root systems can lead to transfers of water between soil layers, on the basis of water potential and resistance. If the subsoil is wet and the surface layers are dry, this process is called hydraulic lift (Dawson, 1993). The reverse process, transfers from wet surface layers to dry subsoil is possible as well and has recently been observed in Machakos (Kenya) (Smith *et al*., 1998; Burgess *et al*., 1998). Although the total quantities involved in these water transfers may be relatively small, it can be important in the competition between shallow and deep-rooted plants. Hydraulic lift can re-wet nutrient-rich dry topsoil layers and thus facilitate nutrient uptake. The reverse process, deep water storage by deep rooted plants after moderate rainfall which only infiltrate into the topsoil, can increase their overall resource capture vis-a-vis shallow rooted plants.

A general solution for the flux F_i into or out of each cell *i* is:

$$F_i = \frac{\sum_{j=1}^{n} \frac{\Psi_i - \Psi_2}{r_i r_j}}{\sum_{j=1}^{n} r_j^{-1}} \qquad \textbf{[13]}$$

where Ψ_i and Ψ_j refer to the root water potential in layer *i* and *j*, respectively and r_i and r_j to the resistance to water flow between the soil layer and stem base. This equation assumes a zero transpiration flux at night.

A more detailed account of hydraulic equilibration through root systems of crop or tree that connect relatively dry and relatively wet zones of the soil was incorporated into WaNuLCAS. The process of 'hydraulic equilibration' is driven by the existence of differences in water potential among the layers (and zones) of a soil profile, and the availability of a conductors in the form of root systems that are connected to the soil.

Implementation requires the following steps:

1. Estimation of equilibrium stem base water potential at zero flux, from the root-weighted average of the soil hydraulic potential in each cell; the proportionality factor consists of root length density and the volume of the cell as other proportionality factors cancel out in the equation.
2. Derivation of the equivalent equilibrium volumetric soil water content in each cell on the basis of this stem base potential for each tree or crop type and the parameters of the pedotransfer function.
3. Calculation of the amount of water involved in the difference between current and equilibrium soil water content (positive differences as 'potential supply' of water, negative ones as 'demand')
4. Derivation of the potential flux as the minimum of a 'cap' ('HydEq_fraction that relates to soil transport constraints that may have to be calibrated to actual data -- default value is 0.1 day^{-1}) of the difference between target and actual volumetric soil water content, and a potential flux that is in accordance with the potential difference, the hydraulic conductivity of the roots, root diameter and root length density and the period of time available (based on the fraction of day that stomata are expected to be closed)
5. Reduction on either the positive or the negative potential fluxes to be in accordance with a zero-sum net process, by calculating the minimum of the total potential supply and total potential demand, and scaling down the cell-specific differences such that total supply matches total demand.
6. Implementing the resulting flux in or out of each cell on a daily time step basis and checking the consistency of the water balance for errors or inconsistencies.

For a 'standard' case of parklands (with parameterization for parkland system in Burkina Faso as simulated by Jules Bayala) the implementation leads to:

1. A total hydraulic equilibration flux through tree roots that is 64% of the tree transpiration,
2. Slight increases for processes that depend on topsoil water content: runoff, soil evaporation
3. A 9% increase in crop water uptake
4. A 22% decrease of tree water uptake (and 10% decrease in canopy interception)
5. A 15% decrease in vertical drainage

These results are only moderately sensitive to the value (arbitrarily) selected for the HydEq_Fraction; values above 0.5 may be unrealistic.

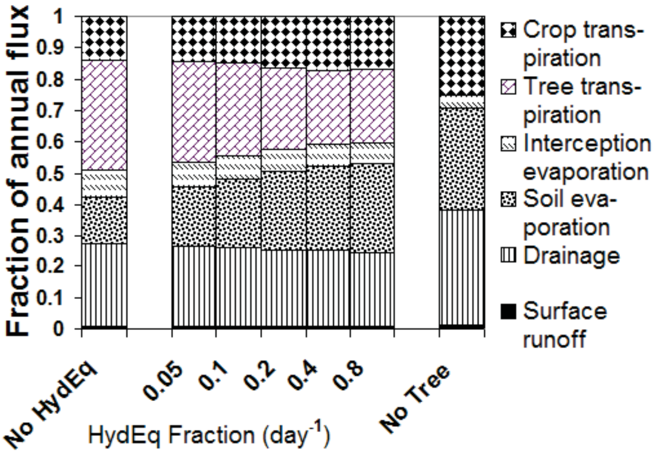


Figure 3.9. Impacts on the water balance of a parkland system with a rainfall of approximately 750 mm year^{-1} of the presence of trees and inclusion of hydraulic equilibration in the model, for a range of values of the (arbitrarily set) HydEq_Fraction parameter.

3.3.4 Implementing a lateral flow component into WaNuLCAS

Earlier versions of the model only considered vertical flow, but evidence from the field experiments in Lampung indicates that even on very mild slopes (4%) a lateral flow component is important (Suprayogo, 2000).

As the model operates at a daily time step, we can not give a detailed account of equilibration and some simplifying assumptions are required:

1. lateral flow is only supposed to occur when incoming water exceeds the 'field capacity' for a given cell in the model; during the lateral flow as well as vertical drainage we assume the soil to operate at saturated hydraulic conductivity,
2. the amount of water leaving a cell in the model, either vertically or horizontally, is equal to the amount of water coming in from above (infiltrating rain in layer 1 and drainage from the layer above in other layers) + lateral inflow from the up-hill neighbouring cell - the amount of water it takes to recharge the profile to field capacity
3. the amount of water flowing across any vertical or horizontal surface is the minimum of three quantities:
    - the amount available for flow (as defined above),
    - the amount that can cross the surface in a day, which depends on saturated hydraulic conductivity per unit area, the size of the surface area to be crossed, and the gradient (1 in the vertical direction, slope%/100 for the lateral flow), and
    - the maximum storage in, plus outflow out of the column below the cell (this is to avoid 'back logging' of water in a dynamic sense; the outflow in a lateral direction is ignored as it will normally be matched by incoming lateral flows)
4. the allocation of total drainage out of a cell over vertical and lateral outflow is based on the relative maximum outflows, but lateral flow can be greater than its nominal share if another constraint on vertical flow so allows; if there is (still) excess water coming into a cell (as lateral inflow exceeds lateral outflow), it is allocated to the water stock in the cell, which can

thus be above field capacity (the next day this will be reflected in a negative value of the potential recharge),

5. lateral flow normally has no influence on the soil water content after the rain event (as the soil will return to field capacity everywhere), but it can have a major impact on the redistribution of nutrients.

Implementing sub-surface lateral flow required the following steps:

1. Splitting the excess (incoming - recharge) water for each timestep into a vertical and a horizontal flow component (**W1**).

   The amount of water leaving a cell is apportioned over one horizontal flow (to the left-hand neighbour) and one vertical one (to the lower neighbour), on the basis of saturated hydraulic conductivity, gradient in hydraulic head (difference in height of neighbouring cells divided by their distance) and surface area through which the flow occurs:

$$Fluxh_{ij} = \frac{Ksath_{ij} HydHeadHor_{ij}\left((depth_i - depth_{i-1})/2\right)}{Ksatv_{i4} xzonew_i + Ksath_{ij} HydHeadHor_{ij}\left((depth_i - depth_{i-1})/2\right)} \quad [14]$$

$$Fluxv_{ij} = \frac{Ksath_{ij} xzonew_i}{Ksatv_{ij} xzonew_i + \sum_i Ksath_{ij} HydHeadHor_{ij}\left((depth_i - depth_{i-1})/2\right)} \quad [15]$$

   with:

$$HydHeadHor_{i1} = \frac{\left(depth_{i,1} - depth_{i-1,1}\right)}{\left(zonew_i + zonew_{I-1}\right)} + origslope \quad [16]$$

   and for $j > 1$ $HydHeadHor_{ij}$ = origslope

2. Accounting for incoming water from above (rainfall in layer 1, vertical drainage from the layer above for the other zones), as well as laterally (**W2**)

   A 'circularity' problem arose when we tried to calculate the lateral flow out of zone 4 as input to zone 3 in the same soil layer. As a first approximation we made the assumption that the incoming lateral flow will **not** have an impact on the subsequent soil water content in a layer (which will return to field capacity if incoming rainfall is sufficient). This first estimate allows us to calculate an estimated drain volume from each cell, which is correct only for zone 4. In a next step, corrections are applied for zone 3, zone 2 and zone 1 in sequence, based on the knowledge of the real incoming lateral flows
3. Defining incoming lateral flow to the simulated zones for all layers (**W3**)

   We assume that the soil up-hill (beyond zone 4) of the simulated zones has similar properties to the soil in the 4 zones: it is assigned the average split over vertical and horizontal drainage found in the simulated zones (see **W1**), and the same rainfall per unit area. The total amount of water coming in is further set by the width of the area generating lateral flow, relative to the total width of the zones considered.
4. Calculating lateral flows of nutrients by multiplying amounts of water moving with the average concentration in soil solution, with an option for 'by-pass flow' of water without exchange with the soil matrix (**N1**)

   The equations followed the same logic as those for vertical leaching, but an option was provided that bypass flow may differ between nutrients already in the N stock of a cell ('matrix') and those in the current in-flow ('macropore'; this includes the fertilizer just added to the soil - if the first rain is mild it will get absorbed by the soil, if the first rainy day is a heavy rain, it may leach down or out quickly depending on the value used for the two by-pass flow parameters).

5. Defining the incoming nutrient concentrations for the incoming subsurface flow (**N2**). The incoming nutrient concentrations for the incoming subsurface flow can be defined as a multiplier of the average concentration of drainage water within the simulated zones.

3.3.5. Run-on and run-off

Surface run-on and run-off are treated in a similar way, but here the conductivity is supposed to be non-limiting as soon as the slope exceeds 0. A RunonFrac parameter determines which fraction of the run-off generated uphill will actually enter the plot. The current routine replaces the old one where the run-off fraction was directly defined from the rainfall amount. In the new version a variable run-off fraction can be simulated, depending on the water content of the soil profile. Essentially two situations can lead to surface run-off:

- daily rainfall plus run-on exceed daily maximum infiltration rate (by setting these values one may try to compensate for typical rain duration per day),
- daily rainfall plus run-on exceed the potential water storage in and outflow from the soil column underneath the surface.

The first type of run-off is typically determined by properties of the soil surface (such as crusting and hydro-phobic properties) and the current infiltration capacity of the soil in the time available for infiltration. The time available for infiltration depends on the duration of the rainfall, the delayed delivery of rainfall to the soil via canopy interception and dripping of leaves (+ stemflow), and the rate at which water ponding on the surface will actually flow to a neighbouring zone or plot. The latter depends on slope. Formally:

$$Rain\_TimeAvForInf = Min(24, Rain\_Duration + Rain\_IntercDelay + Rain\_SurfPondDelay) \quad \textbf{[17]}$$

With

$$Rain\_Duration = \left(\frac{Rain}{Rain\_IntensMean}\right) x min\Big(max\big(0,1 - 3xRain\_INtensCoefVar, Normal(1, Rain\_IntensCoefVar, Rain\_GenSeed + 11250)\big), 1 + 3xRain\_IntensCoefVar\Big) \quad \textbf{[18]}$$

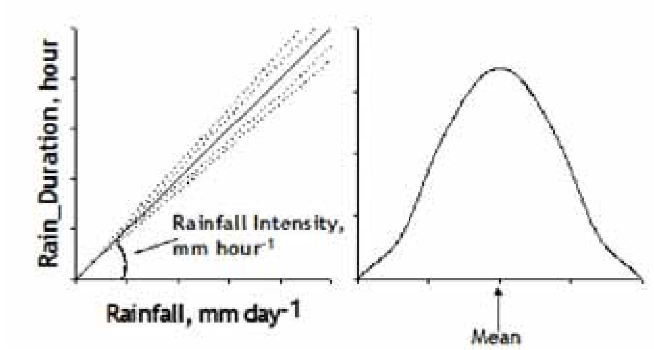


Figure 3.10. Rain Duration that determine the time available for water infiltrated to the soil. Rain duration calculated from rainfall and rain intensity.

$$Rain\_IntercDelay = min\left(Rain\_Max\_IntDripDur, Rain\_IntMultx\frac{Rain\_Interception}{Rain\_IntercDripRt}\right) \quad \textbf{[19]}$$

where the factor IntercMultiplier indicates the maximum temporary storage of water on interception surfaces divided by the amount left at the end of the dripping stage, and the Drip_Rate is expresses in mm hr^{-1}. Default assumptions are Rain_IntMult = 3, Rain_IntercdripRt = 10 mm hr^{-1}, Rain_Max_IntDripDur = 0.5 hr.

and

$$Rain\_SurfPondDelay = \frac{Rain_{PondStoreCp}}{(AF_{SlopeCurr}xRain\_PondFlwRtxAF\_ZoneWidth)} \quad \textbf{[20]}$$

with default Rain_PondStoreCp = 5 mm, and Rain_FlwRt = 10 mm hr^{-1} per m of AF_ZoneWidth

The second type of run off is by the depth of the profile and the saturated hydraulic conductivity of the deep subsoil.

Intermediate situations with sub-surface run-off may build up from 'top down' (higher layers before deeper ones), or 'bottom up' (starting from the subsoil), depending on the specific profile in saturated hydraulic conductivities.

3.3.6. Subsurface inflows of water to plots on a sloping land

In WaNuLCAS 4.0 subsurface in-flows are derived from a 'virtual' soil column uphill (Figure 3.11). This process is only functioning during rainfall events, especially ones that saturate the soil and cause overland or subsurface lateral flow. These are the times, however, that the soil in the 4 zones is in similar 'overflow' mode. An important additional type of lateral inflow may occur during dry periods, when part of the horizontal groundwater flows may come within reach of the roots in the simulated zones. A simple representation of such flows makes use of a 'stock' of groundwater stored uphill, that depends on the 'number of plots uphill' as a scaling factor and the vertical drainage calculated (Figure 3.12).

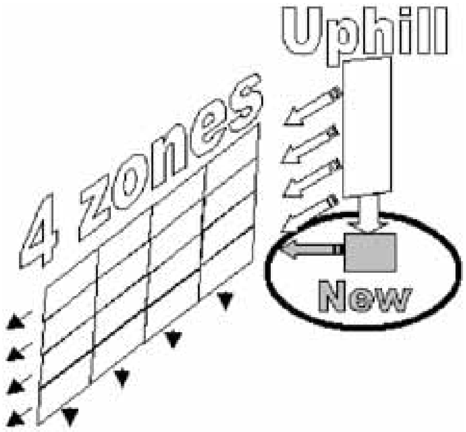


Figure 3.11. General lay out of soil column uphill in WaNuLCAS model.

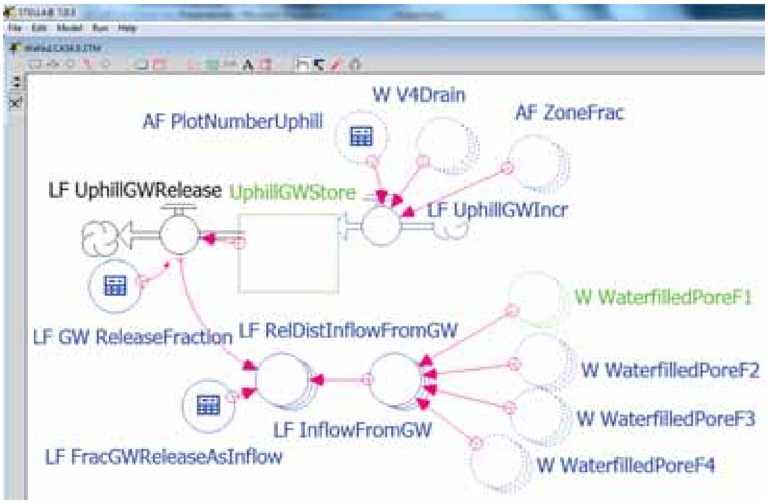


Figure 3.12. Show module of subsurface in-flows from uphill plot in WaNuLCAS.

3.3.7. Dynamics of macropore formation and decay

Formation and decay of macropores has consequences for the bulk density of the ‘soil matrix’, as the mass balance of soil solids has to be conserved. Compaction of the ‘matrix’ may increase the unsaturated hydraulic conductivity of the soil, while the macropores themselves greatly increase the saturated conductivity. If ‘pedotransfer’ functions are used, the change in bulk density (and possibly soil organic matter content) at constant texture can lead to predicted changes in water retention and the unsaturated hydraulic conductivity in a simple way, once the dynamics of macropores are predicted. Where macropores are dominated by cracking, a description of the swelling and shrinking properties is needed as function of soil water content. Where macropores are dominated by roots, earthworms and/or other soil macrofauna their population density and activity should be known, as well as the fraction of macropores temporarily blocked by roots and the rates at which macropores are back-filled by internal slaking of soils and/or bioperturbation.

In WaNuLCAS 4.0 the option is provided for a dynamic simulation of macropore structure. In the Wanulcas.xls spreadsheet, the user can define an initial saturated hydraulic conductivity value that differs (exceeds or is lower then) from the default value predicted by the pedotransfer value. The pedotransfer value reflects a surface infiltration rate in absence of soil biological activities. During the simulation the value will tend to return to this default value, at a rate determined by the S_BDBDRefDecay parameter. The pedotransfer value is used as default, as it reflects measurements in small ring samples without much effect of soil structure. Depending on the ‘foodforworms’ provided by the structural and metabolic organic inputs (with conversions set by the parameters S_WormsLikeLitStruct, S_WormsLikeSOMStruc, S_WormsLikeLitMetab and S_WormsLikeSOMMetab, respectively), and the relative depth impact of the worms on the given location (the S_RelWorm$_{depth}$ parameters determine the relative impact for each soil layer and and S_RelWormSurf the impact on surface infiltration), earthworms can increase saturated conductivity above the default value, but this structure will gradually decay if not actively maintained. With root type 2 during the simulation, anamount of root decay allocated for 'root channels' by calculated root decay on a root biomass basis converted to root volume, and multiplied by an estimate of the fraction of roots that had formed new channels (as opposed to following existing channels, macropores or growing over aggregate surfaces) with conversions set by the parameters S_T_RootFormStrucFrac and S_C_ RootFormStrucFrac for tree and crop root respectively.

With the current structures in place the model is sensitive to variations in saturated hydraulic conductivities (at least in certain parameter ranges, depending on rainfall regime and soil water storage parameters). It may be relatively easy now to make the saturated hydraulic conductivity a dynamic property, e.g. inheriting a system of old tree root channels from a preceding forest phase, with an exponential decay of such channels and a rate of new formation by (tree) root turnover and/or earthworm activity within the layers. Impacts of soil biota on macro-structure of the soil can now be explored.

3.4. Nutrient (nitrogen and phosphorus) balance

3.4.1. Nutrient inputs and outputs

WaNuLCAS release 1.1 only included a nitrogen balance. From release 1.2 onwards, an array 'nutrients' is used with nitrogen as first and phosphorus as second array element.The equations originally developed for nitrogen could be applied to the broader class nutrient, with a number of exceptions which will be noted in the text. In the model, interactions between N and P are only indirect, based on the interaction of both nutrients with plant dry matter production and/ or soil organic matter transformations.

Nutrient inputs to each cell can be based on leaching from higher layers (water flux multiplied with current concentration in soil solution, assuming no bye-pass flow of water to occur). At the bottom of the soil profile nutrient losses by leaching become non-recoverable. For the top layer, inputs can consist of mineral fertilizer at specified times and rates, and from the mineralization of organic matter (on the basis of a process description similar to the Century model; Parton *et al.*, 1994). Total organic inputs are allocated to the various zones on the basis of user-specified weighing functions.

3.4.2. Nutrient inputs

Nutrient (nitrogen or phosphorus) inputs consist of initial amounts in mineral and organic N pools in the soil, initial stocks in the tree and crop seeds, and inputs during the simulation from fertilizer, organic inputs from outside and internal recycling of crop residues and tree litterfall and pruning.

For fertilizer inputs setting the parameters Ca_FertAppYear, Ca_FertAppDOY, Ca_ FertAppRate[Nutrient] can specify the dates and amounts. It is also possible to have two types of organic input as part of management during simulation, Ca_ExtOrgInp. This would need additional parameters to defined the lignin, pholyphenol, N and P content.

Table 3.5. Nutrient (nitrogen and phosphorus) balance at patch level.

In	Out
Initial inorganic N or P stock in soil	Final inorganic N or P stock in soil
Initial organic N or P in SOM-pools	Final organic N or P in SOM-pools
N & P in lateral inflow	N & P in lateral outflow
Fertilizer N or P input	N or P leached from bottom of soil profile
N or P in external inputs or organic material	N or P in harvested crop yield
Atmospheric N fixation (only for N)	N or P in harvested tree components
N or P in crop planting material	Final N or P in crop biomass
Initial N or P in tree biomass	Final N or P in tree biomass

3.4.3. Leaching

Leaching of N (and P) is driven by percolation of water through the soil and the average concentration in soil solution. The latter is derived from the inorganic nutrient stock, the soil water content and the apparent adsorption constant.

An option is provided for flow of water through macropores (e.g. earthworm or old tree root channels), bypassing the soil solution contained in the soil matrix. A multiplier N_BypassMacro*i*[Zone] is used in the leaching equation, which can get different values for each zone and or layer, e.g. to study the effect of earthworm activity mainly in the top layer of zone 1. Default value for N_BypassMacro*i* [Zone] is 1, values less then 1 lead to bypass flow (retardation of nutrient leaching), values above 1 to preferential flow (e.g. possible with rainfall directly after fertilization).

3.4.4. Nutrient (N or P) uptake

The nutrient uptake procedure includes 8 steps (the numbers refer to Figure 3.13):
1) Target nutrient content. The general flow of events starts with the current biomass (dry weight). First of all a 'target N content' is calculated from a generalized equation relating N uptake and dry matter production under unconstrained uptake conditions (De Willigen and Van Noordwijk, 1987; Van Noordwijk and Van der Geijn, 1996). The default equation used assumes a 5% and 0.5% (or Cq_NconcYoung[Nutrient]) N and P target in the young plant, up to a biomass of 0.2 kg m^{-2} (= 2 Mg ha^{-1}) (or Cq_ClosedCanopy) which may coincide with the closing of the crop canopy, and a subsequent dilution of N in the plant, resulting in additional N uptake at a concentration of 1% and 0.1% (Cq_NConcOld[nutrient]). The parameters in this equation can be modified for specific crops. Similarly, for the tree a nutrient target is derived by multiplying the biomass in leaves, twigs, wood and root fractions with a target N or P concentration(T_NLfConc[nutrient], T_NTwigConc[nutrient], T_NWoodConc[nutrient], T_NRtConc[nutrient], respectively.

2 & 3) Nutrient deficit. The target N content is then contrasted with the current nutrient content, to derive the 'Nutrient deficit'. The N deficit can be met either by atmospheric N fixation, governed by a fraction of the deficit on a given day (3a).

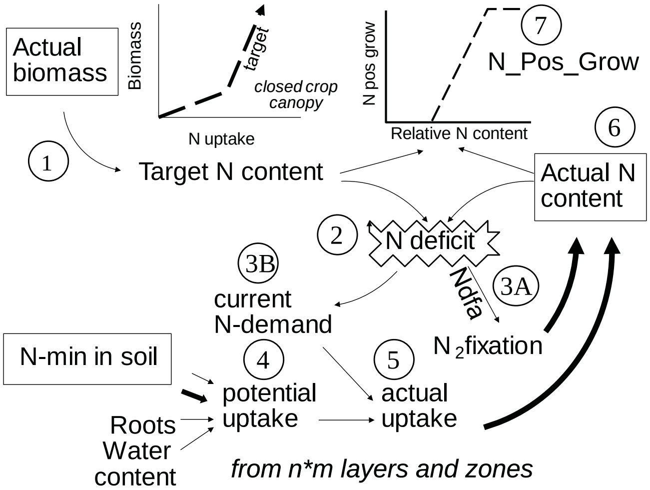


Figure 3.13. Major steps (explained in the text) in the daily cycle of calculating N uptake; a similar scheme applies to P uptake (without N_2 fixation, but with additional options for 'rhizosphere effects'.

$$CN\_Demand = CN\_Deficit * (1 - 0.5 * Cq\_Stage)^2 \qquad [21]$$

The fraction is a user-defined value NDFA (if N supply from the soil is limiting the final percentage of N derived from fixation may be higher then the NDFA parameter chosen - some calibration may be needed to get realistic settings). The N-deficit not met by N fixation as well as the P-deficit lead to Nutrient demand (3b) for uptake from the soil. To avoid too drastic recoveries of uptake where nutrient supply increases after a 'hunger' period, not all of the nutrient deficit can be met within one day.

The fraction of the N deficit covered by the demand decreases with the physiological age of the crop; at flowering (Cq_stage = 1) only 25% of a deficit can be made up within one day and at full maturity (Cq_stage = 2) the uptake response has stopped. The parameters 0.5 and 2 used here have no solid empirical basis, but there is sufficient evidence to suggest that the responsiveness of uptake to past deficits does decrease with plant development.

4) Potential uptake. Potential nutrient uptake U_{ijk} from each cell *ij* by each component *k* is calculated from a general equation for zero-sink uptake (De Willigen and Van Noordwijk, 1994) on the basis of the total root length in that cell, and allocated to each component proportional to its effective root length:

$$U_{ijk} = \frac{Lrv_{ijk}\ \pi D_0 \left(a_1 \Theta_{ij} + a_0\right) \Theta_{ij} H_{ij} N_{stock,ij}}{\sum_k Lrv_{ijk} \left(K_a + \Theta_{ij}\right) \left[-\frac{3}{8} + \frac{1}{2} \ln \frac{1}{R_0 \sqrt{\pi \sum_k Lrv_{ijk}}} \right]} \qquad [22]$$

where Lrv is root length density (cm cm^{-3}), D_0 is the diffusion constant for the nutrient in water, θ is the volumetric soil water content, a_1 and a_0 are parameters relating effective diffusion constant to θ, H is the depth of the soil layer, N_{stock} is the current amount of mineral N per volume of soil, Ka is the apparent adsorption constant and R_0 is the root radius.

For P the same equation applies, but the apparent adsorption constant (the ratio of the desorbable pool and P concentration in soil solution) is not constant but depends on the concentration; parameters for a range of soils are included in the parameter spreadsheet,

5) Actual uptake. Actual uptake S_{ijk} is derived after summing all potential uptake rates for component k for all cells *ij* in which it has roots. Total uptake will not exceed plant demand. The effects of crop N and P content on dry matter production are effectuated via N_pos_grow[nutrient].

$$S_{ijk} = U_{ijk} \frac{\min\left(demand_k, \sum_1 \sum_j U_{ijk}\right)}{\sum_i \sum_j U_{ijk}} \qquad [23]$$

6 & 7) N_Pos_Gro[Nutrient]. Actual uptake and N_2 fixation are both added to the actual N content (6) to complete the process for this timestep. Actual N content of the plant has a feedback on plant growth via N-PosGrow (7). The N-Pos-Grow parameter varies between 0 and 1. The actual N content can stay 20% behind on the N target before negative effects on dry matter production will occur (the N target thus includes 25% ‘luxury consumption’); dry matter production will stop when the N content is only 40% of the N target; between 40 and 80% of the N target a linear function is assumed. The same function is used for tree and crop N-Pos-Grow.

3.4.5. Effective adsorption constants for ammonium and nitrate

Two forms of mineral N occur in most soils, ammonium and nitrate, which differ in effective adsorption to the soil and hence in leaching rate and movement to roots. Microbial transformation of ammonium to nitrate (‘nitrification’) depends on pH, and relatively slow nitrification may reduce N leaching from acid soils. Plant species differ in their relative preference for ammonium relative to nitrate in uptake, with only specialized plants able to survive on a pure ammonium supply; in the current model version such effects are ignored and it is assumed that the ‘zero sink’ solution for nitrate plus ammonium adequately describes the potential N uptake rate for both crop and tree. In the WaNuLCAS model a single pool of mineral N is simulated, but it can cover both forms if a weighted average adsorption constant is used. The potential uptake is inversely proportional to (K_a + W_{theta}), while the leaching rate is inversely proportional to (K_a + 1). Both potential uptake and leaching are dirctly proportional to the Nstock, so the sum over nitrate and ammonium forms of mineral N can be obtained by adding N_FracNO$_3$ times the term with Ka for nitrate plus (1 - N_FracNO$_3$) times the Ka for ammonium, where N_FracNO$_3$ is the fraction of mineral N in nitrate form.

An ‘effective’ apparent adsorption constant K_a for a nitrate + ammonium mixture can be calculated as:

$$N\_Kaeff = -X + \frac{(N\_KaNO_3 + X)(N\_KaNH_4 + X)}{N\_KaNO_3 + N\_FracNO_3(N\_KaNH_4 - N\_KaNO_3) + X} \qquad [24]$$

where X equals 1 for the leaching equation and WTheta for the uptake equation.

In the current version of the model N_KaNO$_3$ and N_K$_a$NH$_4$ are user-defined inputs; in future they may be calculated form clay content and soil pH. The parameter N_FracNO$_3$ is also treated as a user-defined constant for each soil layer; in future it may be linked to a further description of nitrification and be affected by the N form in incoming leachates in each layer and selective plant uptake.

3.4.6. P sorption

In the model the sorbed + soil solution P is treated as a single pool (Figure 3.14A), but at any time the concentration in soil solution can be calculated on the basis of the current apparent absorption constant K_a; this way effects on K_a can be implemented separate from effects on total labile pool size.

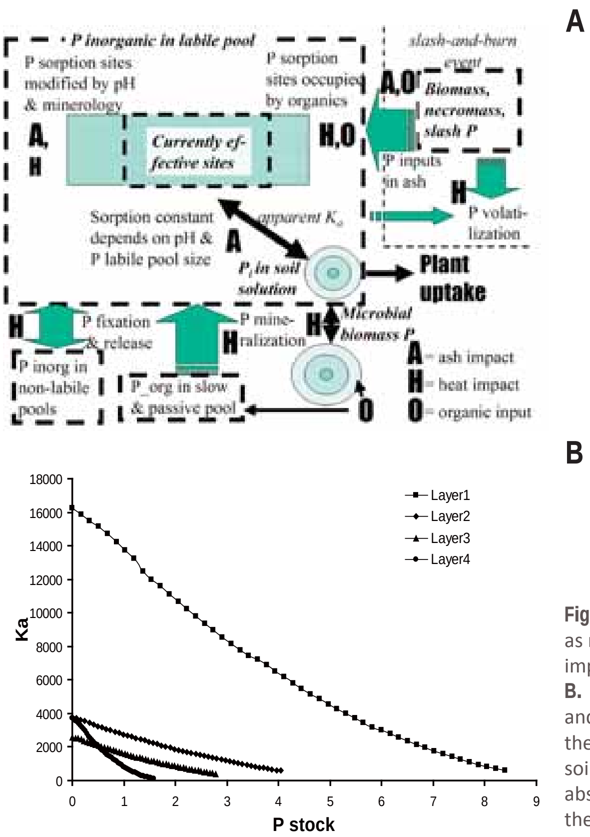


Figure 3.14. A. Conceptual scheme of P pools in the soil as represented in the WaNuLCAS model and potential impacts of ash (A), heat (H) or addition of organics (O); **B.** Example of relations between apparent P sorption and total amount of mobile P in a soil, using data from the database of P sorption isotherms for acid upland soils in Indonesia (names refer to the location, in the absence of more functional pedotransfer functions for these properties).

For P the apparent sorption constant K_a is a function of the amount of mobile P in the soil. In the Wanulcas.xls spreadsheet examples of P sorption isotherms are given for Indonesian upland soils (Figure. 3.14B) and Dutch soil types. The spreadsheet also gives a tentative interpretation to soil test data, such as P_Bray, and translates them into total amounts of mobile P, depending on the sorption characteristics of the soil. This part of the model, however, is still rather speculative. It is based on the assumption that during a soil extraction (e.g. P_Bray2 or P_water) the effect of the extractant on sorption affinity and the soil:solution ratio determine the amount of P extracted from the soil, while non-labile pools do not interact with the measurements. Following this assumption, the relation between a soil test value such as P_Bray2 and the size of the labile pool does depend on the sorption characteristics of the soil.

3.4.7. N_2 fixation from the atmosphere

The option exists for both crops and trees to represent atmospheric N_2 fixation as way of meeting the plant N requirement. The resultant fraction of N derived from the atmopsphere (C_Ndfa or T_Ndfa) can be obtained as model output and equals Nfix/(Nfix + N_uptake).

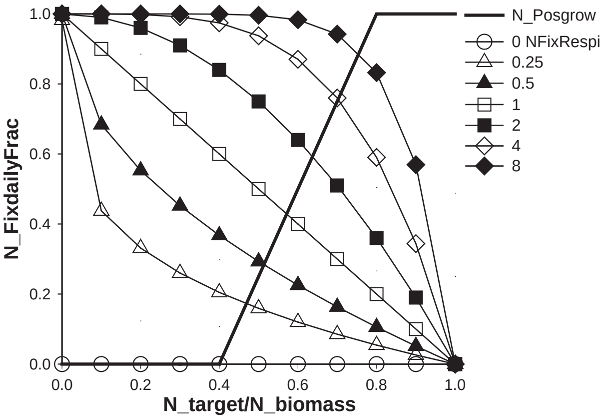


Figure 3.15. Relation between relative N content and daily N_2 fixation as part of plant N deficit, if the N_fixVariable? parameter is set at 1.

N_2 fixation is calculated as a fraction of the current N deficit on any day. If the parameters C_NfixVariable? or T_NfixVariable? are set to 0 (= false), this fraction simply equals the C_NfixDailyFrac or T_NfixDailyFrac parameters set as model input and does not depend on N status of the plant, nor does N fixation have implications for the energy (C) balance of the plant. The part of the N deficit not covered by N_2 fixation drives the demand for uptake from the soil. If one wants to obtain a certain overall NDFA result, the NfixDailyFrac parameter has to be set at a lower (approximately half) value, depending on N supply from the soil, as parts of the deficit not met by uptake from soil on a given day will be included in the calculation for N_2 fixation on the next day (in the extreme case of no N uptake possibilities from the soil the overall NDFA will be 1 regardless of the . NfixDailyFrac parameter setting, as long as this is > 0).

If the parameters C_NfixVariable? or T_NfixVariable? are set to 1 (= true), the fraction of the N deficit covered by N_2 fixation on any day does depend on the N status of the plant and can be constrained by the energy (C) balance of the plant via the ‘growth reserves’ pool (this may implicitly lead to effects of water stress on N_2 fixation). These parameter settings, however, are still in an experimental stage.

If the parameters C_NfixVariable? or T_NfixVariable? are set to 1, N_2 fixation will use resources from the GroRes pools and can be constrained by the availability of these resources in the plant. A conversion factor (DWcost for Nfix) is used to reflect the respiration costs associated with N_2 fixation (roughly 0.01 kg DW per g N), and a maximum fraction of the GroRes pool to be used for N_2 fixation (MaxDWUsefor Nfix) is specified.

3.4.8. Special P mobilization mechanisms

Two further processes were added for P uptake:

- an 'immobile pool' was added to the model, reflecting the difference between total P and available P, and equations were added for a potential mobilizing effect of crop or tree roots on this pool; in the current version there is no (increased) reverse process when the roots disappear,
- roots may (temporarily) influence the adsorption constant in their local neighbourhood by modifying pH and/or excreting organic anions competing for P sorption sites; equations were added for such effects in proportion to the root length density of crop and tree roots; the benefits of a higher potential P uptake are shared over tree and crop on the basis of a 'root synlocation' parameter, reflecting whether the spatial distribution of crop roots in a soil compartment are such that they are mixed or occur in separate clusters. This determines the part of the benefits of rhizosphere modification that will accrue to the species directly influencing the adsorption constant.

The first process (which in principle could be used for nitrogen as well (certain forms of root-induced N mineralization might fall under such a description, although a further reconciliation with organic N pools would be needed), and is governed by:

- N_Nutmob[Nutrient] or relative rate of transfer from the 'immobile' pool of nutrients to the 'mobile' or sorbed pool, due to processes other than root activity (day^{-1});
- N_CNutmob[Nutrient] and N_TNutmob[Nutrient]Relative rate of transfer, per unit crop or tree root length density ($cm\ cm^{-3}$), from the 'immobile' pool of nutrients to the 'mobile' or sorbed pool, due to root activity ($day^{-1}\ cm^2$)

The second process is governed by:

- N_CRhizEffKaP and N_TRhizEffKaP, the proportional reduction of the apparent adsorption constant for P due to root activity of the crop, expressed as fraction of N_KaPdef per unit crop root length density ($day^{-1}\ cm^2$).
- N_RtSynloc, the root synlocation, or degree to which roots of the crop and tree are co-occurring within the various soil layers, affecting the way in which benefits of rhizosphere modification are shared.

3.4.9. N_{15} labeling

The standard version of WaNulCAS no longer includes the sector that represents N_{15} labelling (earlier used by Edwin Rowe in the context of experiments in Lampung). On request, a new labelling sector was constructed that allows N_{15} in any of the 16 cells to be labelled and that tracks the N uptake of crop and tree, plus the relocation within the plant. The module does not yet include the vertical and lateral transfers of labelled N in the soil, nor the soil organic matter or litter layer pools.

3.4.10. Surface movement and incorporation of fertilizer

If there is heavy rainfall shortly after a fertilizer application, fertilizer can move along with overland flow of water, and can leave the plot in surface runoff. To simulate these processes (that can be quantitatively important under specific circumstances), WaNuLCAS now includes the process of dissolution of fertilizer grains and the lateral flow of the remaining fertilizer grains. Dissolved fertilizer will wash into the topsoil with rainfall, and/or can be mixed into the topsoil with a soil tillage operation (similar to the litter -> SOM transfer). Runoff loss from the plot occurs out of zone 1 (and may take two days with surface runoff if fertilizer is used in zone 2 but not in zone 1).

3.4.11. Green House Gas (GHG)

In a recent addition to the model, estimates of nitrogen oxide (N_2, N_2O, NO) emissions are derived, on the basis of mineralization (the 'hole in the pipe' conceptual model; Verchot *et al*., 2004) and denitrification. The form in which the gases emerge from the soil profile depends on the water-filled pore space.

Methane (CH_4) absorption and emissions are closely linked to the available pore space, as the entry of methane from the air into the soil profile by diffusion tends to be the limiting step under dry conditions and wet conditions can lead to net emission from the soil.

The basic for predicting GHG emissions or absorption in WaNuLCAS model is:
1. the daily value of the water-filled pore space, that depends on the soil structure (as influenced by the soil biological activity if we switch the soil structure dynamics to 'on'), rainfall and water use by the vegetation,
2. for N_2O emissions, the dynamics of net nitrogen mineralization as it depends on organic inputs in interaction with mineral fertilizer.

Details for nitrogen oxides

Nitrogen oxide (NO_x) emissions are estimated on the basis of the net N mineralization according to Verchot *et al*. (1999), on the basis of research on deep oxisols in Brasil. The partitioning over nitrous and nitric oxide depends on water-filled pore space. To make it a complete estimate of all gaseous N losses the N_2 emissions are derived as multiplier on the nitrogen oxide emissions, again depending on water-filled pore space.
Verchot *et al*. (1998) derived:

$$NO_x \text{ flux } (\text{ng cm}^{-2} \text{ hr}^{-1}) = 0.954051 * \text{NetMineralization} - 0.093083 \quad \textbf{[25]}$$

with NetMineralization from disturbed samples of the topsoil (10 cm) in mg kg^{-1} day^{-1}

The intercept in the equation creates negative estimates for net mineralization rates less than 0.098 mg kg^{-1} day^{-1}, or 0.0098 g m^{-2} day^{-1} (35.8 kg ha^{-1} $year^{-1}$). There were no data in this range in the original data set, and no negative flux estimates, so we can assign a zero value in this range, or look for an alternative model, without intercept. Refitting the data, a power equation was derived that avoids the intercept and may be safer for use at low mineralization rates:

NO_x flux (ng cm^{-2} hr^{-1}) = 0.7212*NetMineralization$^{1.1699}$
(R^2 = 0.636 versus R^2 = 0.751 for the linear equation) **[26]**

In WaNuLCAS we have:

NetMineralization = Mn2_SomMin1Exch[Zone,N]/(AF_DepthAct1[Zone]*W_BDLayer[1]) **[27]**

but this is actual; the disturbed samples during incubation may be expected to be 1.5 times the actual.

From Verchot *et al*. (1999):

N_2O fraction = (10^(0.030001*100*W_WaterfilledPoreF1[Zone]-1.446925)/
(1+(10^(0.030001*100*W_WaterfilledPoreF1[Zone]-1.446925))))
NO fraction = 1 – N_2O fraction **[28]**

At higher water-filled pore fraction a substantial part of the gaseous emissions will occur as N_2, not measured in the GHG data set. As a first estimate, we can assume that at 100% water-filled pore space (N_2O + NO) form 5% of total emissions, while at 50% water-filled pore space they are 95%. On this basis an N_2 part is added.

The Verchot equation only uses the net mineralization of the topsoil, but was derived from whole-profile chamber measurements of emissions regressed on top 10 cm net mineralization measurements. It thus implies litter mineralization and deeper soil N mineralization and emission processes for (N_2O + NO). The deeper layers may, however, contribute substantively to the overall N_2 flux. As a first approximation we assume that the total N_2 production from the layers below the topsoil has the same relationship with net mineralization as specified above, but that all comes out as N_2.

On this basis, a total gaseous N losses estimate is added to the N balance, while data for predicted N_2O and NO emissions are available for each of the zones in the model.

Details for methane

A midrange estimate for the methane oxidation rate in aerated upland soils is 4 kg ha^{-1} y^{-1} (equivalent to 0.011 kg ha^{-1} day^{-1} or 0.0011 g m^{-2} day^{-1}), while emissions under wet conditions can reach a similar level (Verchot *et al*., 2004). For the model we need one additional parameter that defines the shape of the relationship between water-filled pore space and net emission. Figure 3.16 provides examples for a range of values of the Km parameter.

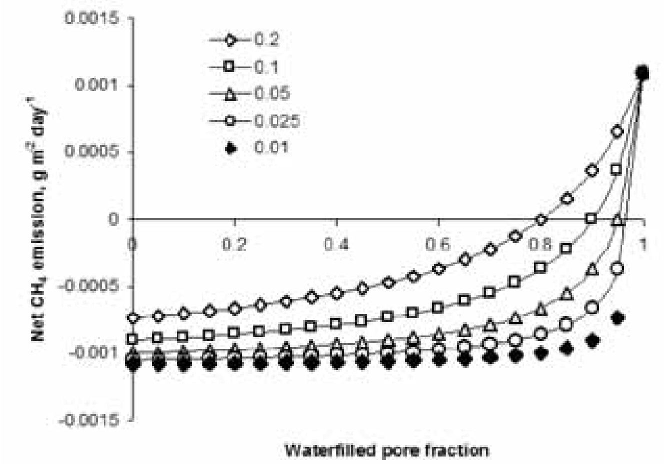


Figure 3.16. Methane flux (negative values indicate consumption, positive ones emission) as a function of the water-filled pore space, for a range of values of the GHG_CH4_Km parameter (a dimension parameter relating to the difference in water-filled pore space (by decrease from fully saturated soil) that causes a 50% change in net emission, within the range defined by highest and lowest flux.

An example

For a simulation on a degraded soil with cassava production and a local tree, we find the following response of gaseous N losses to modifications of the measured rainfall (Figure 3.17):

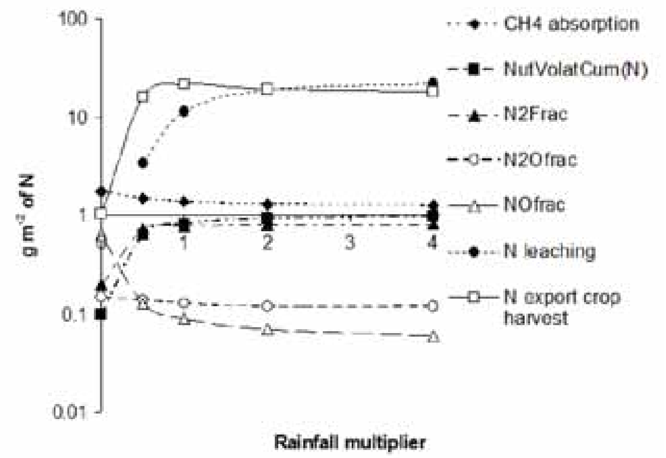


Figure 3.17. Effect of total rainfall, as simulated by using multiplier on daily rainfall amounts, on the gaseous N emissions from a soil (specified over NO and N_2O), leaching and N export from the plot in crop harvests over a 5 year period.

3.5. Root distribution

3.5.1. Crop root length density

Three options exist for deriving the maximum root length density in each cell:

Rt_ACType = 0 user input of maximum root length density for each layer i of zone j. Crop roots can grow and decay following a predetermined pattern, by multiplying a tabulated function [0,1] with this layer-specific maximum value. The maximum value may for example be based on the amount of roots at time of flowering, with a tabulated function describing root growth and decay as a function of crop stage reaching a value of 1 for Cq_Stage = 1 and declining for 1< Cq_Stage <2). Users can modify the form of the graph which (in version 1.1) applies to all crops. Information on the relative root presence during a crop growing season can be ontained from minirhizotron data and analysis of sequential images.

Rt_ACType = 1 crop root length density within each zone decreases exponentially with depth:

$$LrvC(i,j) = Lra(i) DecWDepthC\ e^{(-DecWDepthC 0.5(Depth(i,j)) + (Depth(i,j-1)))} \qquad \textbf{[29]}$$

This function has two parameters:

- Rt_CLra(*i*) = total root length per unit area (cm cm^{-2}), which may depend on zone*i* ;
- Rt_CDecDepth = parameter (m^{-1}) governing the decrease with depth of root length density (at a depth of 0.699/RtCDecDepth the root length density has half of its value at the soil surface). The RtCDecDepth parameter depends on the crop type, and may differ between zones*i*.

Table 3.6. Options for deriving crop root distribution; in WaNuLCAS 4.0

Rt_ACType	Distribution of roots over soil layers	Dynamics of root growth and decay
0	User input value of Lrvmax	RelRoot... as function of crop stage
1	Exponential function (root diffusion into homogeneous soil);RtCDecDepth and maximum Lra(I) as inputs	As in 0
2	As in 1, but Rt_CLra(i) derived from root biomass; Rt_CDecDepth can be modified from the initial input values based on 'local response', modified by Rt_CdistResp. For Rt_CDistResp: 0 => no response, 0-1 => mild response 1 => change in Rt_CDecDepth proportional to inverse of relative depth of uptake > 1 => strong response of root distribution to uneven uptake success of the most limiting resource	Driven by total crop biomass, root weight ratio as a function of crop stage (Cr_RtAlloc), specific root length (Cr _RtSRL) and mean root longevity (Cr_RtHalfLife, in exponential decay); The degree of 'functional equilibrium' response in root/shoot allocation is determined by Cr_RtAllocResp: 0 => no response, 0-1 => fairly late response to stress, 1 => proportional increase of root allocation with stress, >1 => rapid response to stress

The function is evaluated for the half depth of each layer (average of total depth of current and previous layer). The Rt_CLra(*i*) values as a function of crop stage can be obtained by multiplying a maximum value with a crop-stage dependent ratio (as for Rt_ACType = 0).

Rt_ACType = 2 Uses the same exponential root distribution, but involves a 'functional equilibrium' response (Van Noordwijk and Van de Geijn, 1996), allowing the relative allocation of growth to roots to increase when water and/or nitrogen limit plant growth. A simple representation is included of 'local response' by which the vertical distribution of roots is influenced by the relative success of roots in taking up the most limiting resource in upper or lower layers of the profile. Both responses are regulated by a parameter (Cr_RtAllocResp and Rt_CDistResp, respectively) determining the degree of response. These parameter are, however, not easily measured independently and the user may have to explore a range of values. Functional as well as local response can be 'turned off' by setting the responsiveness parameters at 0.

For Rt_AcType = 2, the value of Rt_CLra(*i*) is derived from root biomass multiplied with C_SRL, the specific root length or root length per unit dry weight (m g^{-1}). Root biomass is derived from daily increments in plant biomass, multiplied with the root allocation fraction Cr_RtAllocAct. The latter is calculated from a base-line value Cr_RtAlloc, multiplied with a tabulated function of Cq_stage, and potentially modified to account for functional equilibrium and local response.Cr_RtAllocAct can be modified from Cr_RtAlloc by the minimum of the current water and nitrogen stress in the plant, modified by the parameter Cr_RtAllocResp, as indicated in Table 3.6.

Root decay is implemented by daily removing a fraction of –0.69/Cr_RtHalfLife, where the latter is measured in days and can e.g. be derived from sequential observations with minirhizotrons. In version 1.2 root turnover is **not** influenced by water or nitrogen stress, but such a feedback may be included in future versions.

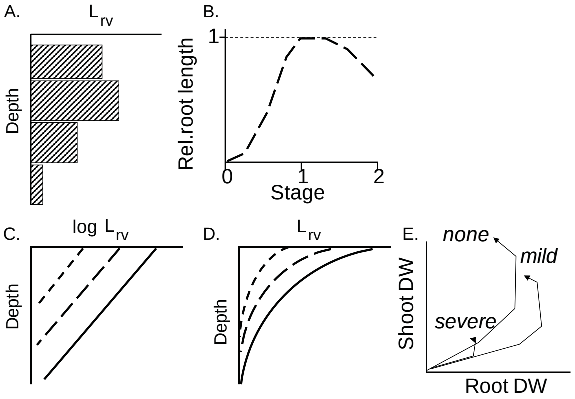


Figure 3.18. Distribution and development of crop root length density; A. Arbitrarily set values of maximum L_{rv} per depth interval (Rt_ACType = 0); B. multiplier to derive daily actual L_{rv} from maximum values per layer (Rt_ACType = 0 and 1); C Exponential decrease of L_{rv} with depth (on log scale), D. *idem* (linear scale) (Rt_ACType = 1); E. Relationship between shoot and root dry weight under no, mild and severe water or N stress (Rt_ACType = 2).

For Rt_ACType 2 it is also possible to modify the Rt_CDecDepth parameter on the basis of current uptake distribution. The response is based on N uptake if C_NPosGro < CW_PosGro, and otherwise by water uptake. We first calculated the relative depth of uptake, by the weighted sum of depth of layer multiplied by uptake per unit root length. For relatively high uptake success in deep layers Rt_CDecDepth will decrease, for success of shallow roots it will increase.

The degree of response is regulated by Rt_CDistResp, as indicated in Table 3.6. When high values of this responsiveness are chosen, the calculated change in root length of an individual layer could exceed the total change in root length from decay and new root growth. We prevent this, by capping off the change based on the proportional change in total root length.

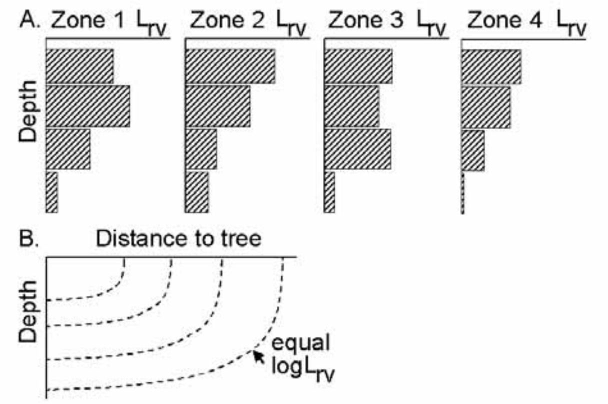


Figure 3.19. Root length density distribution for tree; A. (Rt_ATType = 0) user input of root length density for each cell ij; B. (Rt_ATType = 1) tree roots distributed according to an elliptical function.

3.5.2. Tree root length density

Four options exist for obtaining its value for each cell (zone * depth):

Rt_ATType = 0 user input of root length density for each cell *ij*, and

Rt_ATType = 1 tree roots distributed according to an elliptical function:

$$Lrv(i,j) = LraX0 * RtTDecDepth * e^{-RtTDecDepth\sqrt{Depth_j^2 + (RtDistShape\,HorDist_i)^2}} \quad [30]$$

This function has three parameters:

- T_LraX0 = total root length per unit area (cm cm^{-2}) at a distance X of 0 from the tree stem
- Rt_TDecDepth = parameter (m^{-1}) governing the decrease with depth of root length density (for X = 0, at a depth of 0.699/DecWDepth the root length density has half of its value at the soil surface),
- Rt_TDistShape = dimensionless parameter governing the shape of the tree root system; values less than 1 indicate shallow-but-wide root systems, values of 1 give a circular symmetry, and values > 1 indicate deep-but-narrow root systems.

The function is evaluated for all four corners of each cell and a logarithmic average is determined.

$$Lrv = e^{0.25(\ln(Lrv_{00}) + \ln(Lrv_{01}) + \ln(Lrv_{10}) + \ln(Lrv_{11}))} \quad [31]$$

where the Lrv_{00} .. Lrv_{11} refer to the four corners. (In fact the function is just evaluated once for an elliptically averaged position).

For **Rt_ATType = 2** a functional equilibrium and local response are implemented, as for crop roots, regulated by T_RtAllocResp and Rt_TDistResp. The main difference is that there is no dependence on crop stage, and that the local response has a vertical (Rt_DecDepth) as well as a horizontal (Rt_DistShape) component. Both are regulated by the same Rt_TDistResp parameter.

Rt¬ATType = 3 simulates fine and coarse roots. This option describes the dynamics of fine tree root density in soil voxels (various layers and zones of the soil) and the consequences for coarse roots development to keep up with the transport demand. The dynamics of fine roots is modelled using voxel automata rules. The allocation of fine rootsto a voxel is based on current root length and its previous-day uptake efficiency. A stand alone **STELLA** model is available to learn more about this tree root dynamics option.

3.5.3. Specific root length of tree root systems

For Rt_ATType = 2 we use (inverse) allometric equations to relate proximal root diameters to total root biomass, and drive the specific root length (length per unit biomass) as a function of this diameter (compare section 3.8.4 for aboveground allometric equations.

For a single branched root we can formulate for biomass and length, respectively:

$$T\_Root = Rt\_TWghtDiam1\ Rt\_T\ ProxDiam^{Rt\_TWghtDiamSlope} \tag*{[32]}$$

$$Rt\quad TLength = Rt\quad TLengDiam1\ Rt\quad T\ ProxDiam^{Rt\_TLengDiamSlope} \tag*{[33]}$$

For a root system consisting of a number of roots of different diameters, we assume that the cumulative frequency distribution of proximal root diameters can be approximated by:

$$CumFreq = \left(T\ ProxDiam / T\ ProxDiam_{max}\right)^{T\ ProxGini} \tag*{[34]}$$

where TProxGini is a parameter equivalent to a Gini coefficient as used in studies of income distribution, and hence (using D in stead of TProxDiam, a_1 for T_DiamRtWght1, b_1 for T_DiamSlopeRtWght, a_2 for T_DiamRtLeng1, b_2 for T_DiamSlopeRtLeng and n for T_ProxGini):

$$Freq(D) = dCumfreq / dD = T\ ProxGiniD_{\max}^{(-T\ ProxGini)} D^{(T\ ProxGini-1)} \tag*{[35]}$$

We can derive the total dry weight T_Root (Wt) from 42 and 44 as:

$$T\_Root = \int_0^{D_{max}} Freq\ W\ dD = a_1 n\ D_{max}^{-n} \int_0^{D_{max}} D^{b1+n-1} dD = a_1 n D_{max}^{b1} / (b_1 + n) \tag*{[36]}$$

Similarly, for the sum of proximal root diameter squares, we obtain:

$$SumD_r^2 = nD_{max}^2 / (2 + n) \tag*{[37]}$$

and the equivalent single proximal root diameter as the square root of $SumD_r^2$.
Equations (36) and (37) can be used to derive the maximum proximal root diameter D_{max}:

$$D_{\max} = \left(W_t\left(b_1+n\right)/\left(a_1 n\right)\right)^{1/b1} = \left(sumD_r^2\left(2+n\right)/n\right)^{0.5} \tag*{[38]}$$

Relations between W_t and $SumD_r^2$ can now be obtained as:

$$W_t = \left(\frac{(a_1 n)}{(b_1+n)}\right)\left(\frac{sumD_r^2(2+n)}{n}\right)^{b1/2} \tag*{[39]}$$

and

$$SumD_r^2 = n/\left(2+n\right)\left\{W_t\left(b_1+n\right)/\left(a_1 n\right)\right\}^{2/b1} \tag*{[40]}$$

Similarly, from (42) and (44) we obtain Rt_TLenght (L_t) as:

$$L_t = \left(a_2 n\right)/\left(b_2+n\right)\left\{SumD_r^2\left(n+2\right)/n\right\}^{b2/2} \tag*{[41]}$$

and from [50] and [51]:

$$L_t = \left(a_2 n\right)/\left(b_2+n\right)\left\{W_t\left(b_1+n\right)/\left(a_1 n\right)\right\}^{b2/b1} \tag*{[42]}$$

Finally, the specific root length SRL is obtained as function of W_t

$$SRL\left(W_t\right) = L_t/W_t = \left(a_2 n\right)/\left(b_2+n\right)\left\{\left(b_1+n\right)/\left(a_1 n\right)\right\}^{b2/b1} W_t^{b2/b1-1} \tag*{[43]}$$

Equation (53) is used in the model.

3.5.4. Root diameter and mycorrhiza

Tree and crop are likely to differ in root diameter. As root diameter has an effect on the potential uptake rate, an 'average' root diameter in each layer and zone is needed for the uptake functin and a way to estimate the equivalent effective root length of each component at such a diameter. A simple approach is used in WaNuLCAS, based on De Willigen and Van Noordwijk (1987) and Van Noordwijk and Brouwer (1997), comparing roots of different diameter on the basis of the product of root length and SQRT(root diameter); this method of averaging makes the uptake function least sensitive to diameter (see Van Noordwijk and Brouwer, 1997; Figure 3.20)

$$RtDiamAV_{ij} = \left[\frac{Rt\_CLrv_{ij}\sqrt{Rt\_CDiam} + Rt\_TLrv_{ij}\sqrt{Rt\_TDiam}}{Rt\_CLrv_{ij} + Rt\_TLrv}\right]^2 \tag*{[44]}$$

Based on this rule for adding roots of different diameter on the basis of the square root of their diameter, we can also get a first approach to the effects of mycorrhizal hyphae. The total length of hyphae can be derived from the fraction of roots that is mycorrhizal (Rt_MCInfFrac or Rt_MTInfFrac), and the length of hyphae per unit length of mycorrhizal root (Rt_MCHypL or Rt_MTHypL).
The effective root length then can be derived as:

$$EffLrvC_{ij} = LrvC_{ij}\left[1 + \frac{Inffrac\ .HypLeng\ .\sqrt{HypDiam}}{\sqrt{RtDiamC}}\right] \qquad \textbf{[45]}$$

which effectively converts the mycorrhizal hyphae into an equivalent length at the diameter of the roots. This option is provided for both crop and tree.

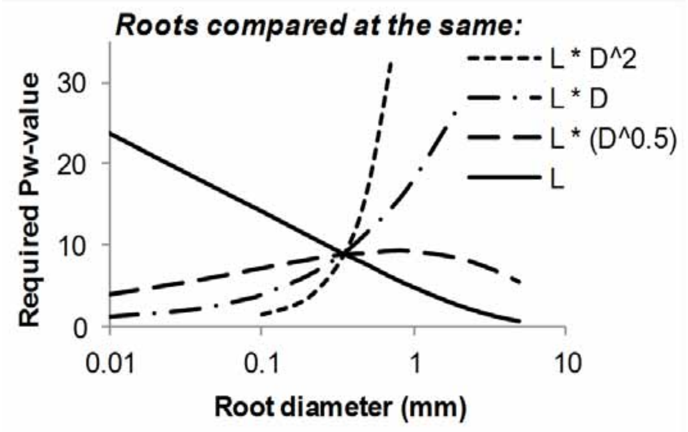


Figure 3.20. Effect of root diameter on potential uptake when root systems of different diameter are compared at equal length, root surface area or volume (weight); the smallest effect of root diameter exists when root length times the square root of the root diameter is used (Van Noordwijk and Brouwer, 1997).

3.6. Light capture

Light capture is calculated on the basis of the leaf area index of the tree(s) and crop (T_LAI[tree] and C_LAI) for each zone, and their relative heights. In each zone the parameters T_CanLow[tree], T_CanUp[tree], C_CanLow, C_CanUp indicate lower and upper boundaries of crop and tree canopy, respectively. LAI is assumed to be homogeneously distributed between these boundaries.

Light capture by the trees is separated in light captured by branches (based on their vertical projection area in the 'branch area index' or BAI) and leaves (based on leaf area index, LAI), while only the LAI part of total capture is used by the plants. This option allows to account for shading by trees when they are leafless, as *Faidherbia albida* is during the crop growing season. The ratio of BAI and LAI depends on the canopy architecture, leaf size and age of the tree. For older trees with small leaf sizes BAI can be similar to LAI (Van Noordwijk and Ong, 1999).

The current approach has evolved from that in WaNuLCAS where only a single tree plus crop component was simulated. In that case, three strata were distinguished in the canopy: an upper one (with only one type of leaves), a mixed one (with both types of leaves present) and a lower one (with one only) (Figure 3.21).

If light capture of *n* plants is to be accounted for in the same way, a total of *2n-1* canopy layers should be distinguished, with all boundaries determined by either an upper or a lower boundary of one of the components. In WaNuLCAS we chose, however, to use only *n* canopy layers, using only the upper bounds of the component canopies as determinants. This choice means that for any plant type the light capture above its canopy is correctly calculated, but in the sharing of light within a canopy layer the calculations assume that all plant types present in that layer have leaves spread evenly within that layer.

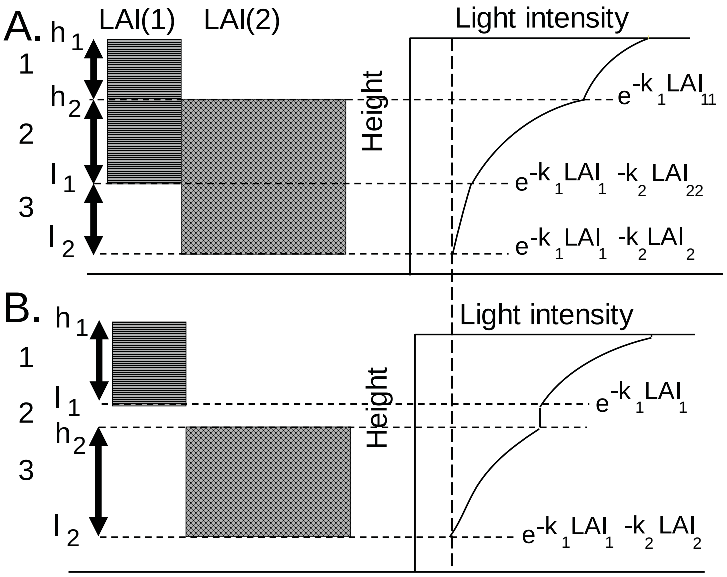


Figure 3.21. Light capture in a two-component leaf canopy, as used in WaNuLCAS; three zones can be distinguished: an upper zone with only one species, a middle one with both and a lower one with only one (usually not the same as in the upper zone); total light capture in the shared zone may be apportioned relative to the leaf area index of both species in that zone (compare Kropff and Van Laar, 1993).

The errors made in this approximation are generally less than 1% of incoming radiation, but under specific parameter conditions light capture by a component can have a relative error of up to 25% (Figure 3.22)

Specifically, the following steps are taken in WaNuLCAS in the daily calculations per zone:

1. sort the four values (three trees plus crop) of upper canopy boundary (CanU_{pi}),
2. calculate the canopy boundary values CanBound_j from these ranked values (for *j* = 1 take the highest, for *j* = 4 the lowest CanUp value)
3. calculate the LAI of each plant component *i* in each canopy layer *j* by assuming the leaf area to be evenly distributed within its canopy:

$$LAI_{ij} = LAI_i\left(MIN\left(CanUp_i, CanBound_j\right) - MAX\left(CanLow_i, CanBound_{j+1}\right)\right)/\left(CanUp_i - CanLow_i\right) \qquad \textbf{[46]}$$

CanBound5 is assumed to be zero (any value smaller or equal to min(CanLow*i*) will give the same result).

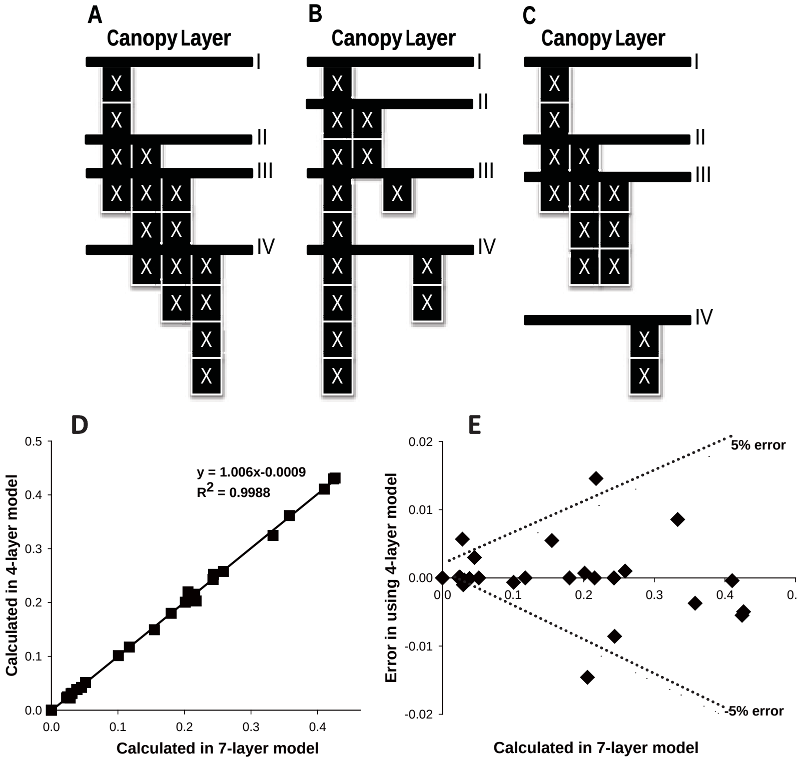


Figure 3.22. A, B and C Three examples of canopy distribution of four plant types within a given zone and the way they are represented in the canopy layers for calculating light capture; D and E Comparison of light capture calculations per component (tree or crop) according to the 4-layer canopy model used in WaNuLCAS and that in a theoretically more correct 7-layer model.

4. calculate total light capture in each canopy layer on the basis of Beer's law for all components, starting at the top and accounting for light captured above the layer:

$$TotLightCap_j = 1 - \sum_{k=1}^{j-1} TotLightCap_k - e^{-\sum_i (kLLight_i * LAI_i - kBLight_i * BAL_i)} \quad [47]$$

where the kLLighti and kBLighti values represent the light extinction coefficients for leaves and branches, respectively.

5. share the light captured in a layer over the contributing components,

$$LightCap_{ij} = TotLightCap_j \frac{kLLight_i LAI_{ij}}{\sum_i (kLLight_i * LAI_i - kBLight_i * BAI_i)} \quad [48]$$

6. accumulate the light captured by each tree or crop over the various canopy layers.

Our choice for n rather than 2n-1 layers introduces an inaccuracy in step 5 in as far as the lower canopy boundaries of the various components within a layer do not coincide.

3.7. Crop growth

3.7.1. Basic Relations

Major relationships in the daily cycle of calculating crop biomass accumulation (Figure 3.23) are:

1. calculation of crop leaf area index on the basis of shoot biomass, leaf weight ratio (LWR, leaf weight as fraction of total shoot weight) and specific leaf area (SLA, m^2 g^{-1}),
2. calculation of canopy height on the basis of biomass and physiological stage (assuming height growth to stop at flowering),
3. calculation of the relative light capture on the basis of LAI of both tree and crop (see section 3.5),
4. calculation of the potential growth rate of the crop for that day, by multiplying relative light capture with the light use efficiency (dry matter production per unit light captured) and maximum net growth rate (kg m^{-2} day^{-1}), which is an input to the model and can be derived from more physiologically explicit models of potential crop growth under the given climate. The maximum net growth rate is supposed to include respiration losses for maintenance of existing tissues as well as for the formation of new ones. There is an option to specifically define maintenance respiration. This option enabled weed to be shaded by tree (see 3.7.3 on Maintenance Respiration)
5. calculation of transpirational demand on the basis of this light-limited potential growth rate and a potential water use efficiency (dry matter production per unit water transpired), which will depend on the crop species,
6. calculation of whether actual water uptake can meet this transpirational demand (see section 3.3); the factor CW_PotGro is determined as the ratio of actual water use and transpirational demand,
7. calculation of the N limitations on growth on the basis of CN_PotGro (see section 3.4),
8. calculation of real dry matter production as the product of C_PotGroRed and the minimum of CN_PosGro and CW_PosGro.
9. calculation of litterfall, if the actual LAI of the crop exceeds the maximum (C_LAImax, which is crop type dependent), a proportional part of the stem and leave biomass is transferred to the litter layer.

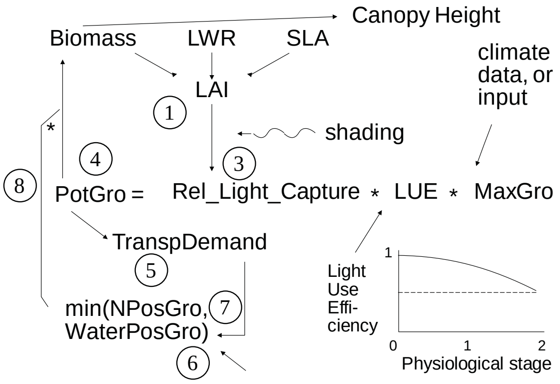


Figure 3.23. Major relationships in the daily cycle of calculating crop biomass accumulation.

The model thus assumes that under N deficiency crops keep their potential transpiration rate, but have a reduced actual water use efficiency (dry matter production per unit water use). Under water stress, N uptake will be reduced as biomass accumulation slows down and thus demand is decreasing.

3.7.2. Deriving stage-dependent potential growth rates and allocation to harvested organs for situations without shading, water or nitrogen deficiency

A number of the allocation functions depends on the 'physiological age' of the crop. A basic length of the vegetative and generative stage is given as model input (Cq_TimeVeg[season] and Cq_TimeGen[season], respectively) for each crop. These values are used to re-scale time into 'crop-age'; for environments where temperature is a major variable, crop development can be driven by a temperature sum rather than by time.

In WaNuLCAS the following allocation functions depend on crop stage:

- harvest allocation (Cq_HarvAlloc),
- specific leaf area (Cq_SLA),
- leaf weight ratio (Cq_LWR),
- relative light use efficiency (Cq_RelLUE).

These functions can be user-defined from experimental data of crops growing in full sunlight in the local climate with adequate supply of nitrogen and water, or from more detailed physiological models. Figure 3.24 and 3.25 give examples of basic allocation functions derived from the Wofost model (data provided by Dr. P. de Willigen, AB-DLO Haren the Netherlands), using climate data for Lampung (Indonesia) and 'standard' parameter settings for cassava, (upland) rice, maize, groundnut and cowpea. From data such as this taking the ratio of green leave and total biomass can directly derive LWR. To obtain RelLUE the growth rate (dW/dt) is divided by the estimated light capture (on the basis of LAI - this calculation requires parameter values for SLA and light extinction coefficient)

The sheet 'Deriving Crop Gowth' in the WaNHELP.xls spreadsheet takes the following steps in converting output of a potential crop growth simulation (daily predicted biomass in leaves, stems and storage organ(or grain)), into the input parameters which are used in the 'Crop Growth' spreadsheet.

Input columns:

DwLv[time]= leaves biomass in dry weight (kg ha^{-1} day^{-1})
DwSt[time]= stem biomass in dry weight (kg ha^{-1} day^{-1})
DwSo[time] = storage biomass in dry weight (kg ha^{-1} day^{-1})
SLA[time] = specific leaf area in m^2 g^{-1}
Cq_kLight = light extinction coefficient, as fixed value over time

Derivations:

DwTot[time] = total dry weight biomass = DwLv + DwSt + DwSo
GroMax = maximum daily increment in aboveground plant biomass = max(DwTot) (kg ha^{-1} day^{-1})
LWR[time] = leaf weight ratio = DwLv[time]/(DwLv[time] + DwSt[time])
TimeVeg = length of vegetative stage period = time of flowering or last day before first value of DwSt is recorded
TimeGen = length of generative stage period = time to harvest - TimeVeg
Stage = Increased of plant growth stage = time/TimeVeg for time<TimeVeg and (1 + (time - TimeVeg)/TimeGen) for time $\geq$ TimeVeg

Deriving apparent light use efficiency:

Calculate daily increment in total dry weight (logarithmic average over preceding and subsequentperiod):
BiomInc[time] = exp(0.5*(ln (dDwTot/dt)preceding + ln (dDwTot/dt)subsequent)
Calculate daily relative light capture, the factor 10 000 converts from ha to m^2:
RelLightCap[time] = 1 - exp(-k * DwLv * SLA/10000)
Calculate relative daily growth per unit light capture (relative to the maximum growth rate, which implicitly reflects the radiation level):
RelLUE[time] = (dDwTot/dt)/(GroMax* RelLightCap)

Deriving apparent remobilization from stems and leaves and allocation to storage organs:

Daily increment in storage organ: dDwSo/dt
Apparent remobilization from leaf and stem dry weight during generative stage:
Remobfrac[time]= (dDwSo/dt - dDwTot/dt)/(DwLv + DwSt)
Value of Remobfrac which can be used for the whole growing season: max(Remobfrac[time])
Daily allocation to storage organs:
HarvAlloc[time] = (dDwSo/dt)/((dDwTot/dt) + Remobfrac * (DwLv + DwSt))

Converting time-dependent variates into crop stage dependent ones:

The derived parameters LWR[time], SLA[time], RelLUE[time] and HarvAlloc[time] are now converted to crop-stage dependent equivalents:

To convert the data which may have unequal intervals into the equal-interval format expected by **STELLA**, the stage dependent variates are plotted in a graph with stage as X-axis. Manually we read in values at constant intervals (helped by grid-lines in the graph) into the columns Cq_CLWR[stage], Cq_CSLA[stage], Cq_CRelLUE[stage] andCqCHarvAlloc[stage], respectively.

As illustrated in Figure 3.26 for maize, the daily interpolation does not exactly match the Wofost input (based on 10 day recording intervals), but errors in daily rates as well as cumulative amounts stay within generally acceptable limits (5%); towards the end of the crop development, however, the Wofost model (as well as proper field data) show a decline in total dry weight as respiration exceeds photosynthesis; in WaNuLCAS we do not explicitly represent respiration losses or account for negative growth rates, but the losses are accounted for by assuming a lower net growth rate in the preceding period. This approach, however, leads to deviations in the harvest index.

In WaNuLCAS a reverse procedure is used to derive the daily potential growth rate (Cq_from the actual relative light capture (based on crop LAI as well as shading) multiplied by Cq_RelLUE and Cq_GrowMax. [This assumes that potential growth rates are proportional to light capture] Effectively we allow the user to use this simulated data for modified crop phenology (changes in TimeVeg and TimeGen) as well as modified maximum growth rates, as simple ways to apply it to modified climatic conditions. If large modifications are made it would be safer to derive fresh inputs from a potential crop growth model for the new situation.

If no potential growth simulations are available, the user may enter other types of estimates of the biomass of leaves, stems and storage organs into the spreadsheet and otherwise follow the procedure outlined.

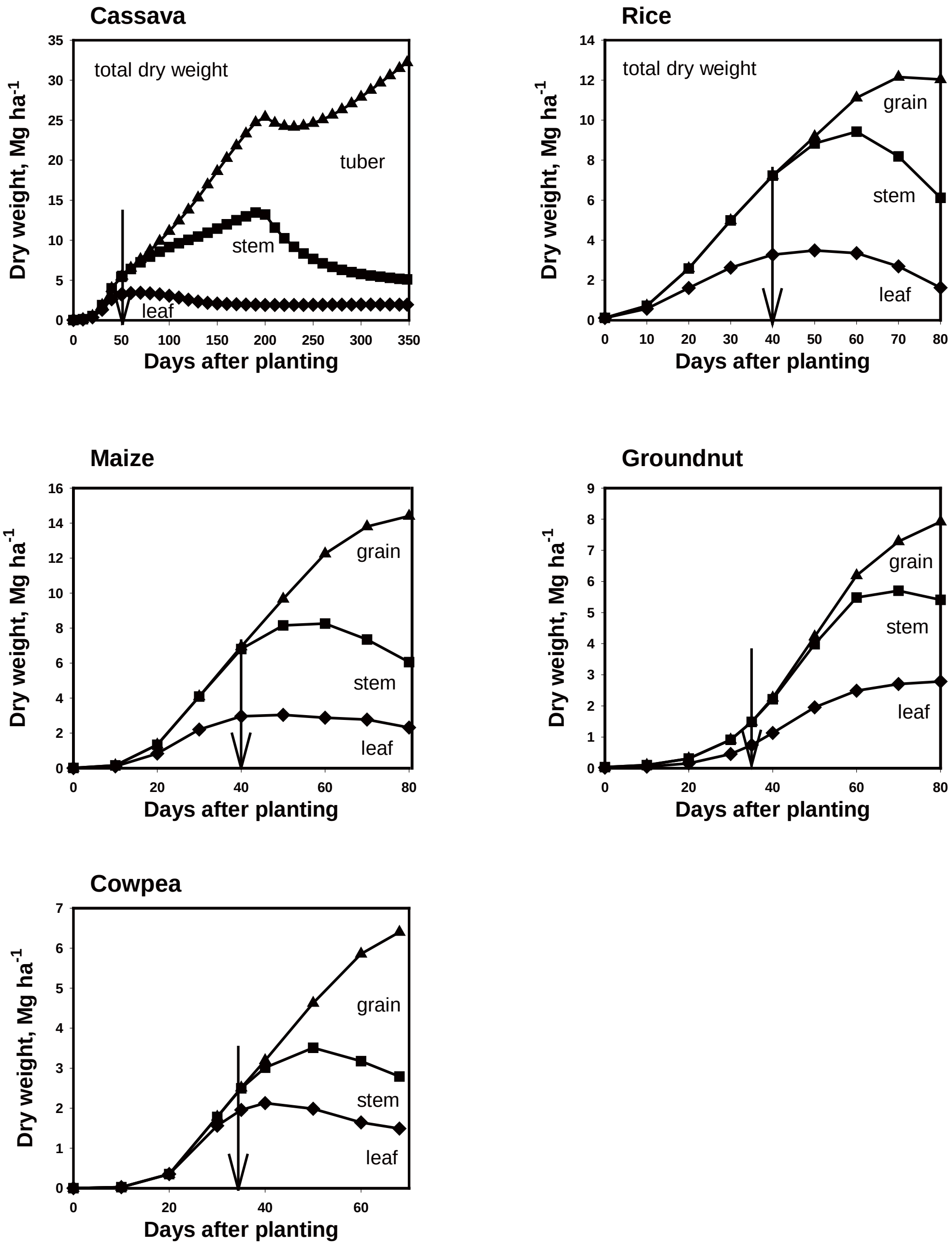


Figure 3.24. Examples of basic allocation functions derived from the Wofost model using climate data from Lampung (Indonesia) and 'standard' parameter settings for cassave, (upland) rice, maize, groundnut and cowpea (data provided by Dr. P. de Willigen, AB-DLO Haren the Netherlands). Arrows denote the starts of generative stage (Cq_Stage=1).

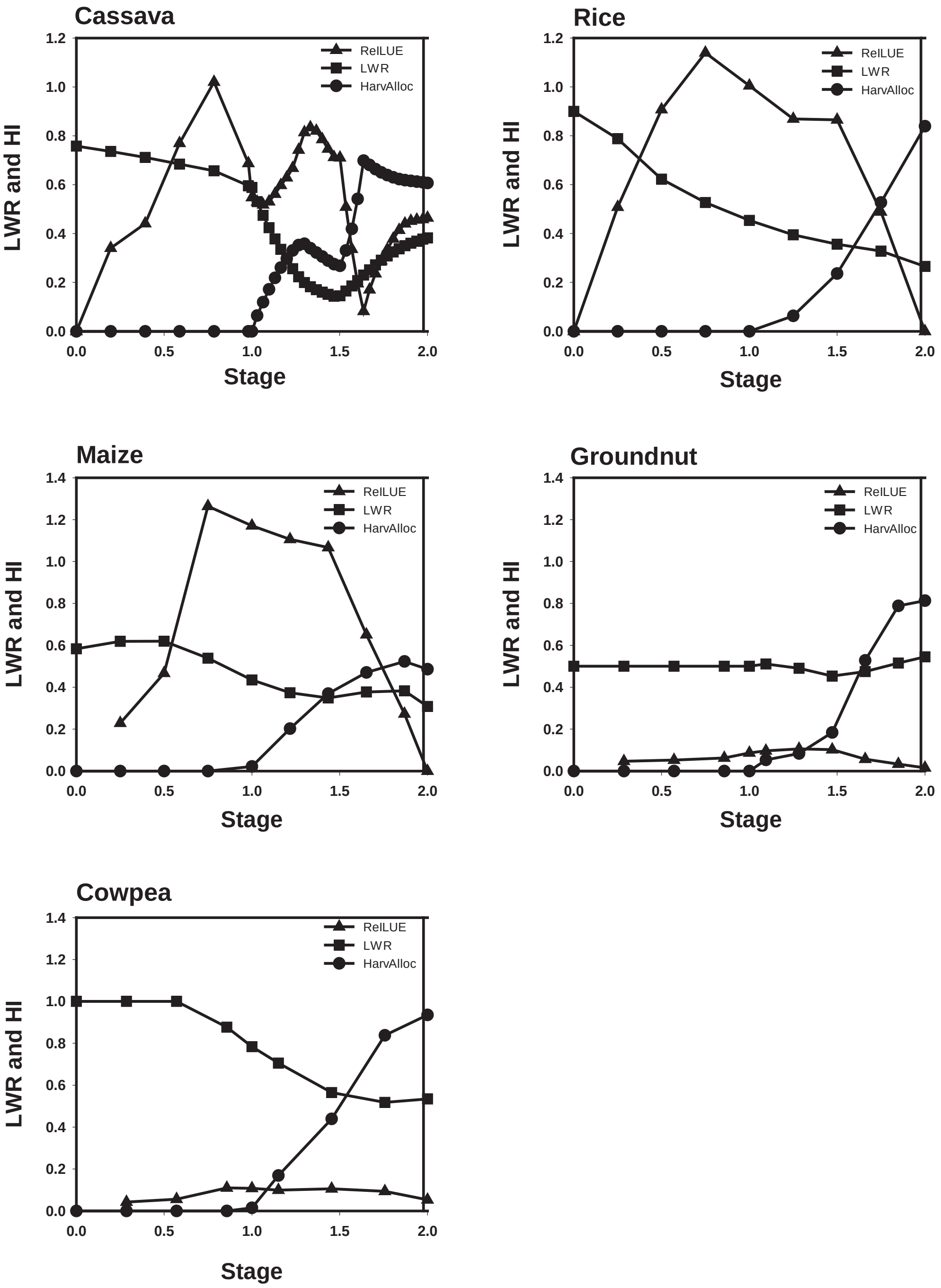


Figure 3.25. Leaf weight ratio, harvest allocation and relative light use efficiency rate as a function of time for the model output of figure 3.24.

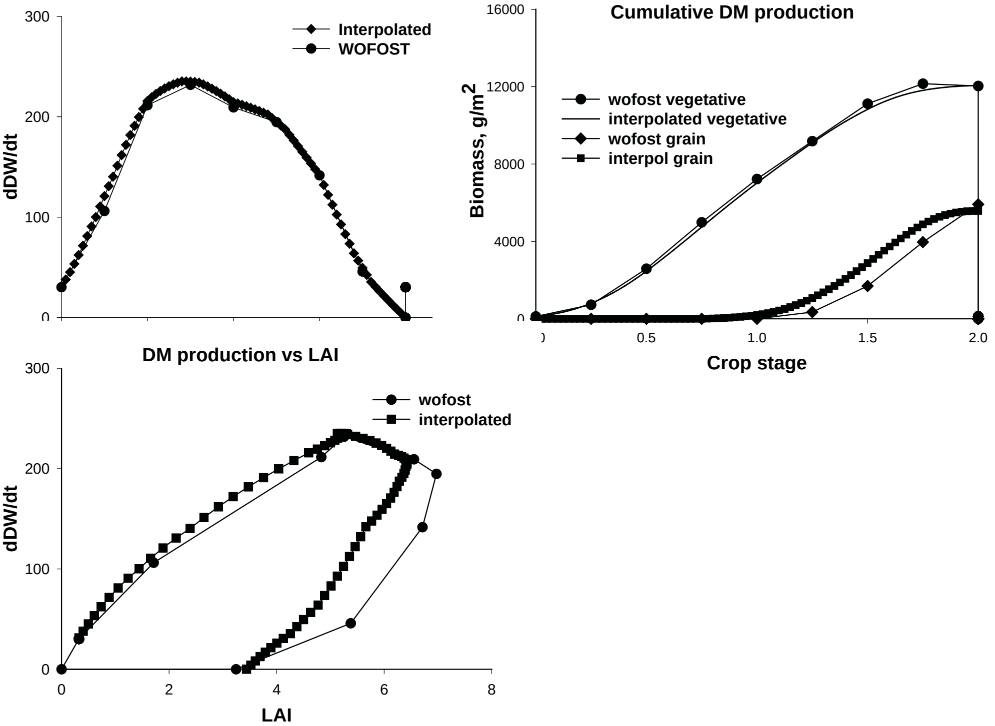


Figure 3.26. Comparison of potential production as derived per 10-day interval from the WOFOST model, and the daily interpolated values derived in the Wanulcas.xls spreadsheet: A. daily growth rates, B. accumulative dry matter production, C. trajectory of the relation between growth rate and LAI.

3.7.3. Maintenance respiration

Maintence repiration in WaNULCAS is specifically address the ability to ‘shading out weeds’. We use two additional concepts:

1. maintenance respiration from the growth reserve pool, at a rate of X % of current biomass per day, that leads to a ‘compensation point’, or light level below which the crop will start to decrease in reserves,
2. if growth reserves (dry weight) are zero the plant will die

We implement it by using the following additional parameters:

C_ApplyMaintResp? is a on/off switch for applying the maintenance respiration; for a default value of 0 all the rest is ignored

C_RespPerBiomass is the relative use of resources for maintenance respiration per unit biomass

C_RelRespRt is the relative weighting factor for roots as part of total biomass as used for maintenance respiration

C_RelRespStLv is the relative weighting factor for stem&leaves as part of total biomass as used for maintenance respiration

C_RelRespCurrHarv is the relative weighting factor for developing fruits as part of total biomass

as used for maintenance respiration
C_RelRespGroRes is the relative weighting factor for growth reserves as part of total biomass as used for maintenance respiration
C_RespTemp is a graphical relation between temperature and maintenance respiration
C_GroResMobFrac is the fraction of growth reserves that is used for growth of plant organs such as stems&leaves on a daily basis

These parameters are set within the **STELLA** model and not yet part of Crop Library in Excel.

3.8. Tree growth

3.8.1. Tree growth stage

For the trees a physiological growth stage is defined in the [0 - 1] range for the vegetative stage up to the first flowering event, and in the [1 - 2] range for flowering and fruit ripening. After fruit ripeness the tree returns to stage 1 (rather than dies, as is the case for 'annuals'). The parameters governing tree growth stage are:
T_TimeVeg - duration [days] of initial vegetative period before first flowering
T_InitStage - tree growth stage at start of simulation
T_StageAfterPrun - growth stage to which trees are returned after a pruning event
T_TimeGenCycle - duration [days] of a flowering - fruit ripeness cycle
T_FlowerDOYbeg - first day of year at which flowering can occur
(provided stage = 1.0)
T_FlowerDOYends - last day of year at which flowering can occur
T_FruitAllocFrac - fraction of current growth resources in the tree allocated to developing fruits
T_FruitHarvFrac - fraction of ripe fruit biomass and nutrients harvested from the plot

When the trees are pruned, all fruit biomass is removed from the tree and may be partly harvested from the plot, along with vegetative pruned biomass, as governed by the T_PrunHarvFrac.

When the growth stage reaches 2.0, all fruit biomass is removed from the tree, and the T_FruitHarvFrac part of it is harvested from the plot, the remainder returned as mulch.

On a daily basis a fraction of the T_Fruit biomass pool can be removed by frugivory and fruit abortion, as governed by T_frugivory&abortionFrac, and returned to the soil as mulch.

3.8.2. Canopy and support structure

WaNuLCAS includes a simple description of canopy shape, aboveground biomass production and litterfall; these rules are applied if the T_ApplyFBARules? switch is put at 0. In the model, the calculated aboveground tree biomass increment is first of all allocated to a buffer of 'carbohydrate reserves' and is allocated from there to make:

- a canopy, consisting of leaves and small branches (<2 cm diameter),
- a support structure, consisting of supporting branches and a trunk,
- replacement of leaves and branches transferred to 'litterfall'

$$\Delta Biom = \Delta Canopy + \Delta Support + \Delta Litterfall \qquad [49]$$

The allocation over canopy and support structures depends on the size of the tree. while litterfall is related to the development of 'bare branches' in the support structure.

Within the canopy, the increment in leaf biomass is calculated from:

- LWR (leaf weight as fraction of total biomass in the canopy),
- SLA (specific leaf area, or leaf area per unit leaf weight).

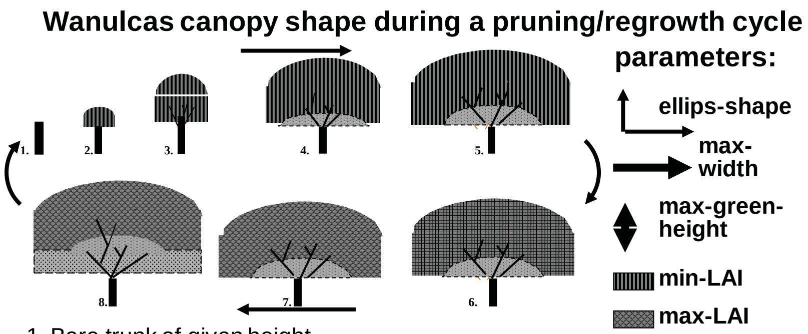
$$\Delta Leafarea = \Delta Canopy * LWR * SLA \qquad [50]$$

A half ellipse on a stick (forming an 'umbrella' approximates tree canopy shapes, with as parameters:

- R, radius (half of the width),
- H, height (measured above the bare stem section); the canopy height consists of a green part and, above a certain total height, a bare section,
- S, shape, or ratio of radius and height of the half ellipse (or of width and total height of a full ellipse; S = R/H; S = 1 indicates a circle),
- LAI-canopy (leaf area index within the canopy), which can vary between LAI_{min} and LAI_{max}.
- An alternative formulation that is activated when T_ApplyFBARules? = 1 is described in section 3.8.4.

3.8.3. Daily cycle of calculations

The sequence of events during a pruning/regrowth cycle is illustrated in Figure 3.27. In the first stages of regrowth after pruning, growth is based on the carbohydrate reserves in the bare trunk which remained after pruning and is thus dominated by the fraction which can be converted daily. Once green leaves start to function, the carbohydrate reserve pool can be replenished and growth rates can increase. At first the canopy extends with a minimum LAI within the canopy, LAI_{min}. Both width and height can be calculated from the total leaf area, LAI_{min} and the shape of the ellipse (which is assumed to be constant, but could be made size-dependent if more specific data are available).



1. Bare trunk of given height
2..4. Lateral expansion of canopy with a fixed LAI-canopy, and constant LWR inside the canopy, and constant width/height ratio
5. When canopyheight exceeds max-greenheight, litterfall ~ inner ellips
6,7. When maximum canopy-width is obtained, the LAI inside the canopy may increase to its maximum value, still at constant LWR
8. Beyond this point the canopy will increase in height, with concommittant litterfall and formation of 'thick stem' category

Figure 3.27. Tree canopy shape during a pruning - regrowth cycle

$$R = Leafarea / LAI_{\min} \qquad [51]$$

$$H = R / S \qquad [52]$$

By the time the calculated canopy height exceeds the 'green-canopy height', litterfall is supposed to start. New biomass production continues to be allocated to leaves (T_LWR) and stems (1 – T_LWTR), but only the stems is added to tree biomass and the new leaves are simply replacing litterfall. If the maximum canopy width is reached, the canopy can gradually increase in LAI from LAI_{min} to LAI_{max}.

$$\Delta height = leafgrowth / (LAI_{\max} * Maxwidth) \qquad [53]$$

If LAI_{can} reaches LAI_{max}, the canopy will gradually move upwards. All new leaf growth is offset by litterfall. The increment of tree-height follows from:For the 'support structure' a tabulated function can be used to allocate dry weight. Alternatively, allometric equations based on fractal branching properties can be used (not yet).

Pruning events are described in section 3.10.7.

3.8.4. Tree diameter and allometric biomass allocation rules

A number of allometric biomass equations (of the general form: $Y = aD_b$) is commonly used to relate biomass in specific fractions (total aboveground, leaves+twigs, branches, total belowground) or total root length to the diameter of the main stem, or the equivalent diameter of all proximal roots (for belowground application see section 3.5.3). The spreadsheet 'Functional Branch Analsysis' (FBA) that is released as a companion to WaNuLCAS provides a way to derive parameters of these allometric equations on the basis of parameters that can be relatively easily observed (without large scale destructive sampling).

In WaNuLCAS we use the general biomass - stem diameter relation in inverse form to derive stem diameter from the total tree biomass as it develops on the basis of the growth rules. The relation

$$T\_BiomAG = T\_BiomDiam1\; T\_StemDiam^{T\_BiomDiamSlope} \qquad [54]$$

can be inverted to obtain

$$T\_StemDiam = \left(T\_BiomAG / T\_BiomDiam1\right)^{1/T\_BiomDiamSlope} \qquad [55]$$

Aboveground biomass of a tree may decrease, e.g. due to litterfall or pruning, without causing a direct reduction in stem diameter. In WaNuLCAS we therefore keep track of the stem diameter via the maximum aboveground biomass obtained so far in the simulation. The T_StemDiam parameter is used as indicator for the readiness for tapping latex in rubber trees, and to drive allometric equations for other properties:

$$T\_TargetLeafTwig = T\_LeafTwigDiam1\; T\_StemDiam^{T\_LeafTwigDiamSlop} \qquad [56]$$

$$T\_BiomBranch = T\_BranchDiam1\; T\_StemDiam^{T\_BranchDiamSlope} \qquad [57]$$

$$T\_LargeWood = T\_Wood - T\_BiomBranch \qquad [58]$$

If the T_ApplyFBARules? switch is on (value = 1), the transfer of dry weight and nutrient resources from the canopy biomass to the T_Wood pool is driven by the difference between T_TargetLeafTwig and current T_CanBiom.

3.8.5. Tree phenology

In WaNuLCAS we treat the physiological water use efficiency (dry matter production per unit water used, in situations without nutrient stress) as a constant, to be specified for each crop type or tree species, but not varying with plant age. The model predicts that this water use efficiency will be reduced under nutrient stress, as such a stress (beyond a tolerance limit) affects dry matter production but not water use. The main differentiation in physiological water use efficiency implemented so far is a generic difference between C3 and C4 crops.

Measurements of instantaneous water use efficiency at leaf level, e.g. with IRGA equipment, generally show considerable variation in this efficiency between individual leaves, partly linked to position of leaves in the canopy and leaf age. During ‘ageing’ leaves tend to become less efficient for a number of reasons. Where trees differ substantially in average age of current leaves (e.g. in a comparison between trees that are evergreen and those that regularly shed leaves in a dry or cold season) a difference in ‘average leaf’ water use efficiency should be expected. One step further would be to keep track of the average age of current leaves in a canopy and assign a water use efficiency on the basis of a generic ‘ageing’ function.

In calculating the average age of a leaves in a canopy we may simply impose a phenological pattern on a tree based on the time of year that leaf flush starts and litterfall is completed (either the same dates every year, or differentiated according to weather records and e.g. a temperature sum), or trigger these events by relations inside the model. Since WaNuLCAS version 2.1 rules are included for a drought-induced litterfall, with a minimum waiting period for leaf re-emergence if the water stress disappears (e.g. as a consequence of reduced demand after litterfall).

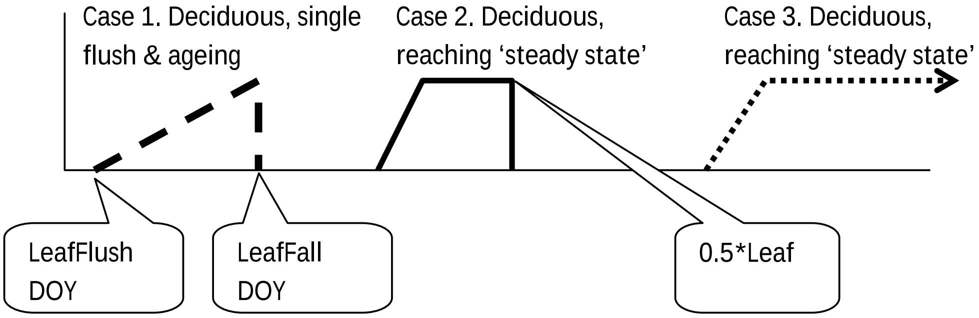


Figure 3.28. Three parameters are used to describe the leaf age over time, allowing the 3 cases to be paremeterized.

3.8.6. Cumulative litterfall

If the initial length of a link (section of stem or branch between two branching points) is L_{min}, and its initial diameter D_{min}, a linear increase of expected link length with diameter can be described as:

$$L(D) = L_{\min} + a_1 (D - D_{\min}) \qquad \textbf{[59]}$$

If we may assume that the distance between branching points does not vary with time or growth stage of the tree, an increase in distance reflects branches being dropped. If L(D) = 2 L_{min} one branch will have dropped, for L(D) = 3 Lmin two branches etc.; from equation [59] we can expect that for a diameter increment from D_x to $D_x+\delta$ an additional number of branches of $\delta\, a_l / L_{min}$ will be dropped (ignoring the discrete character of these events and describing their expected means for a population of branches). We may assume that the branch dropped was the smaller one of the two branches at that branching point, so it had a diameter of:

$$D_{x2} = \left((1-q) D_x^2 / \alpha\right)^{0.5} \qquad \textbf{[60]}$$

where a and q are parameters of the fractal branching process.

The biomass of the dropped branches can be estimated from the overall biomass equation Biom = BiomD1 D^b and the total biomass dropped can now be derived by integrating from D = D_{min} to D = D_{max}:

$$CumLittfall(D0) = \int_{D\,min}^{D\,max} (a_l / L_{min})\, BiomD1\left\{\sqrt{(1-q)}D^2 / \alpha\right\}^b dD =$$

$$= \frac{a_l\; BiomD1((1-q)/\alpha)^{0.5b}}{L_{min}(b+1)}\left(D_{max}^{b+1} - D_{min}^{b+1}\right) \qquad [61]$$

For any D_{max} value more then 2.4 Dmin the error made when ignoring the D_{min} term in the equation is ignored is less than 5% and for $D_{max} > 3.7$ Dmin it is less than 1%. For cumulative litter fall based on dropped branches with the leaves they originally carried, we thus derive an approximate allometric equation with power b+1, if the D_{min} term can be ignored. As the power of the cumulative litterfall equation is higher that that for standing biomass, cumulative litterfall will exceed standing biomass beyond a certain stem diameter (Figure 3.29A); the position of the cross-over point is (again, if the D_{min} term can be ignored):

$$D = \frac{L_{min}(b+1)}{a_l((1-q)/\alpha)^{0.5b}} \qquad \mathbf{[62]}$$

and is this independent of BiomD1 and decreases with increasing slope of the link length diameter relationship a_l (if $a_l = 0$ there is no litterfall).

From equation [62] we can derive the current litterfall for a small diameter increment above D_0 as:

$$AllocLit(D) = \frac{dCumLittFall}{dD} = \frac{a_l BiomD1((1-q)/\alpha)^{0.5b}}{L_{\mathrm{min}}} \qquad \mathbf{[63]}$$

while allocation to the Biomass pool will be:

$$AllocBiom\ (D) = \frac{dBiom}{dD} = bBiomD\ 1\ D^{b-1} \qquad \mathbf{[64]}$$

Thus, the relative allocation of new photosynthate to litterfall will increase with D_0 according to the relative allocation to litterfall thus approaches 1, posing a limit to the maximum size of a tree (Figure 3.29B).

$$RelLitFallAlloc(D) = \frac{a_l((1-q)/\alpha)^{0.5b} D}{a_l((1-q)/\alpha)^{0.5b} D + bL_{min}} \qquad \mathbf{[65]}$$

In the actual implementation of litterfall according to these allometric rules, we take into account that actual litterfall e.g. due to drought stress, can be ahead of the amount due according to equation [62]. If so, new leaves and twigs can grow unimpeded until the former canopy biomass is regained.

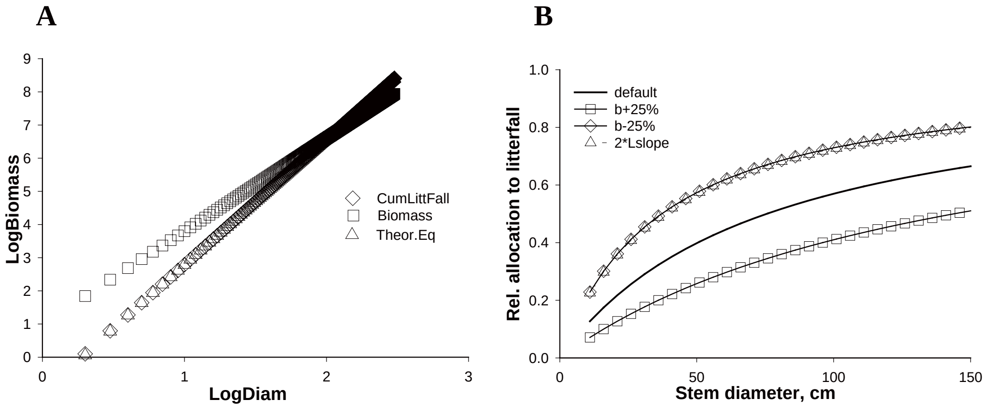


Figure 3.29. A. Comparison of biomass and cumulative litterfall as a function of stem diameter comparing a numerical integration with results of eq.[54]; **B**. Relative allocation of current biomass production to litterfall as a function of stem diameter for a default parameter set and in situations where the slope of the biomass allometric equation is increased or decreased by 25%.

3.8.7. Tree products

A number of tree products can be harvested and removed from the plot:

- tree prunings (e.g. for use as fodder), governed by T_PrunHarvestFrac
- fruits, governed by d T_FruitHarvIndex, fruiting itself governed by tree stage (see Tree Growth Stage)
- latex, coming directly from the T_GroRes pool; the model user can define a minimum tree diameter required for tapping and the fraction of growth resources harvested on a tapping day
- wood, governed by T_WoodHarvestFrac and T_WoodHarvDay

3.8.8. Oil palm growth

A new option is available to simulate fruiting mechanism in oil-palm (Figure 3.29). Palms differ from most dicotyledonous trees in a number of ways that are relevant for the current model: they have a much more rigid development pattern in which leaves are formed and emerge continuously (rather than with the seasonality or flushing of many trees), gradually forming a stem which normally does not branch and that does not show secondary growth in diameter (as the leaf area supported by the stem is virtually constant over time there is no need for more transport or support tissue, but inversely, the lack of secondary meristems in the existing stem can be a constraint on branch development). Flowers are formed in axillary buds, one for every leaf and have a long development trajectory that starts much before the adjacent leaf emerges, and that includes phases where the sex of the flowers is determined, in response to physiological conditions in the palm. The long development phases from bud to flower to ripe fruit causes a large number of developing bunches to be present on the same palm, interacting in their demand for growth resources.

This general pattern applies to oil palm, coconut, peach palm and date palm. For the sago and sugar palm, however, flower development is delayed and the palm stores large amounts of internal resources; in sago these are directly harvested (and the palms loose all their value in years that the climate-related trigger for flowering is expressed), for sugar palm the stored resources are intercepted on their way to the developing flowers, once the palm starts to flower (and flowers develop in a top-down sequence, opposite to their age).

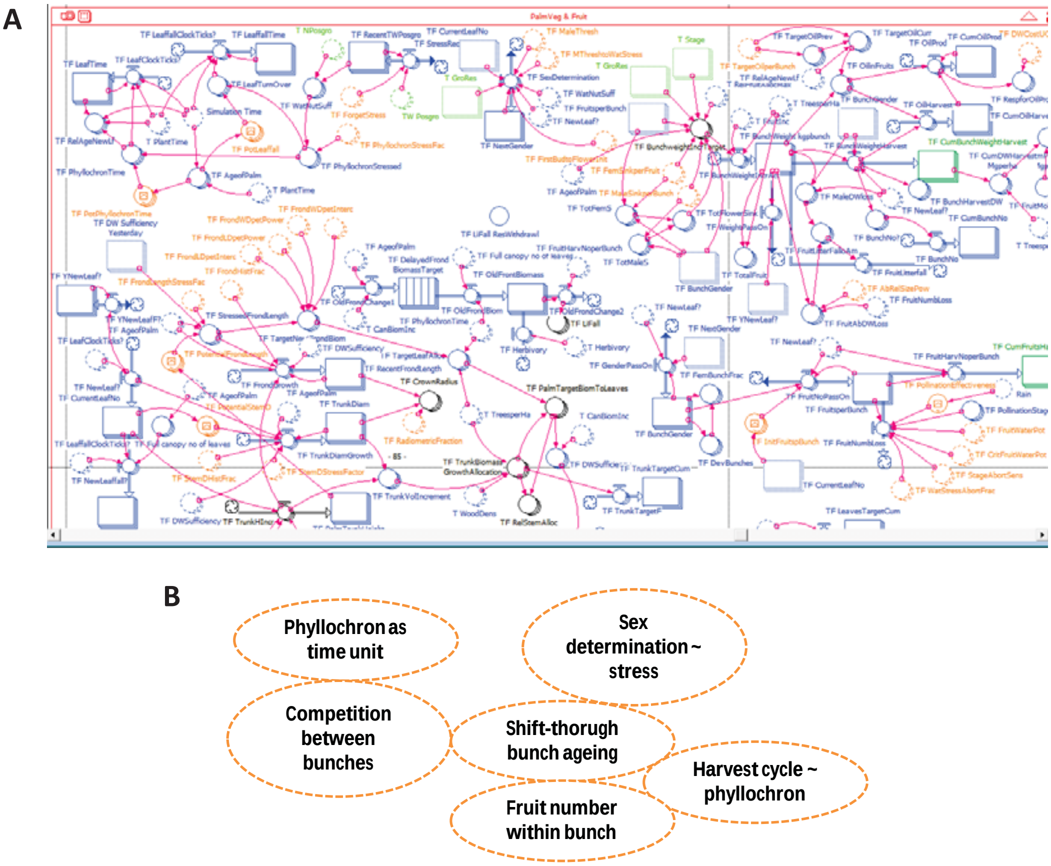


Figure 3.30. Diagram (A) and schematic map (B) of the new tree fruit module developed to represent palm fruit development in the various bunch stages.

Focussing on oil palm and leaving further model adaptations to other palms for a later treatment, the following model elements were identified for the model:

- **phyllochron** time keeping: the time interval between the emergence of two leaves, or phyllochron, determines the basic unit of time for floral and fruit development as well. For current oil palm germplasm a phyllochron unit is about 14 days.
- **sex determination** of flowers is related to the internal condition of the palm, based on its internal growth reserves, as well as in response to current water stress; as in the model the switch between male and female bunches is set at a single day, we do it on the basis of a moving average of the past water stress levels; because of the link with internal growth

reserves the module can account for the tendency to male flowers caused by tapping for palm wine, as is common practice in W. Africa.

- **simultaneous development and resource competition** between the various male and female flowers and bunches present at any point in time, with an age-dependent relative sink strength,
- **abortion** of individual fruits in a bunch, in response to water stress,
- **book keeping** of the dry weight and fruit number individual bunches as they shift through the stages from flower to ripe bunches,
- **harvest of one (potential) bunch at the end of each phyllochron unit.**

Figure 3.30 shows the palm oil module in WaNuLCAS, sink strength for male and female bunches and the sensitivity to drought stress leading to fruit abortion depend on bunch development stage.

3.8.9. Harvesting latex or resin from tress

Tapping rubber (*Hevea brasiliensis*) or jelutung (*Dyera costulata*) trees for their latex, or *Acacia senegalensis* for its gum-arabic or any other tree for its resin, implies a direct drain on the Growth Reserves in the tree. WaNuLCAS can simulate the consequences for tree growth and yield of products in the short and longer time frames, of various intensities and frequencies of tapping. As implemented in WaNuLCAS 4.0, the assumption is made that all N and P stay behind in the tree and only dry matter is affected. The description is given here in terms of tapping rubber, but the same routines could be used for other tree products after adjustment of parameter values.

The conversion of Tree Growth Reserves (T_GroRes) into harvested product is described as a two-step process: formation of latex and building up a stock of latex, and the actual tapping (Figure 3.31). The first conversion is controlled by inherent properties of the trees (T_Rubber?, an on/off switch that is part of the tree library), and a dynamic allocation fraction (T_LatexFormAlloc) that depends on a number of tree parameters (than can be differentiated for rubber clones) such as a maximum mobilization fraction, bark thickness and a saturation feedback if the latex stock (T_LatexStock) approaches its maximum capacity (Figure 3.32).

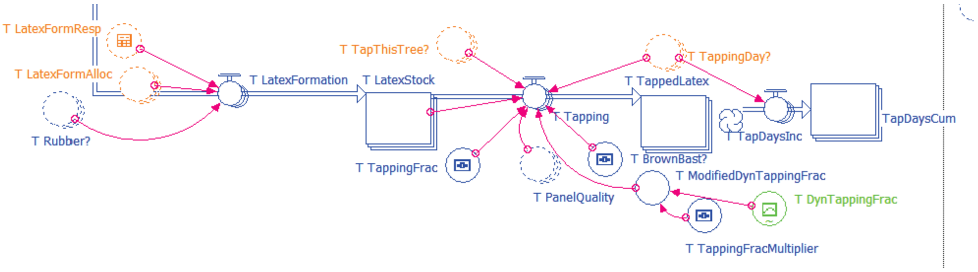


Figure 3.31. Latex formation diagram in WaNuLCAS model

The second step, tapping into the actual tapping (T_TappedLatex) pool can influence the rate of latex formation. There are a number of controls here:

- Whether the tree has reached the minimum girth at which tapping starts (T_GirthMinforTappingcm),
- Whether the date matches the annual tapping period (e.g. avoid dry season and wettest period),
- Whether it is a 'tapping day', depending on the tapping schedule selected (T_TappingDay?) (Figure 3.33),
- Whether there is sufficient 'tapping panel' left (bark below the maximum tapping height that has not been tapped before, or has sufficiently recovered since an earlier tapping cycle, governed by a recovery rate) (T_PanelQuality) (Figure 3.34),
- Whether the panel is affected by the 'BrownBast' condition (a fungal infection) (T_BrownBast?),

Whether recent tapping events provided economically attractive returns to labour (this is based on a comparison of labour investment, dry weight of latex obtained and prices for a day of labour and a kg or dry rubber). This function reflects farmer decisions to selectively tap as long as it gives adequate yield or otherwise rest a tree and focus on others in the same stand (T_TapThisTree?) (Figure 3.31).

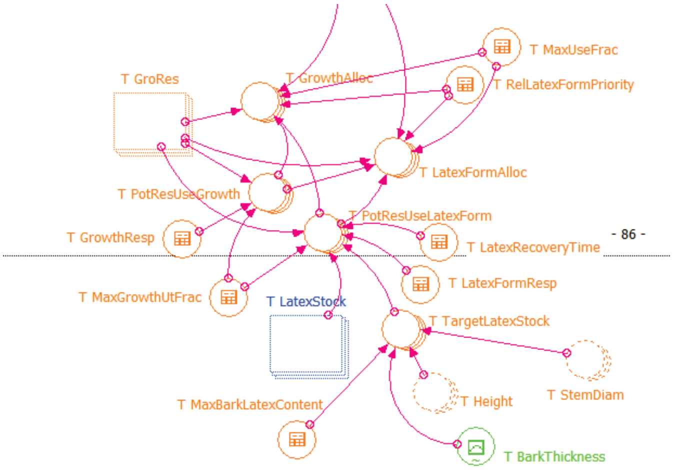


Figure 3.32. Diagram that show number of tree parameter controls a dynamic of latex allocation fraction (T_LatexAllocForm).

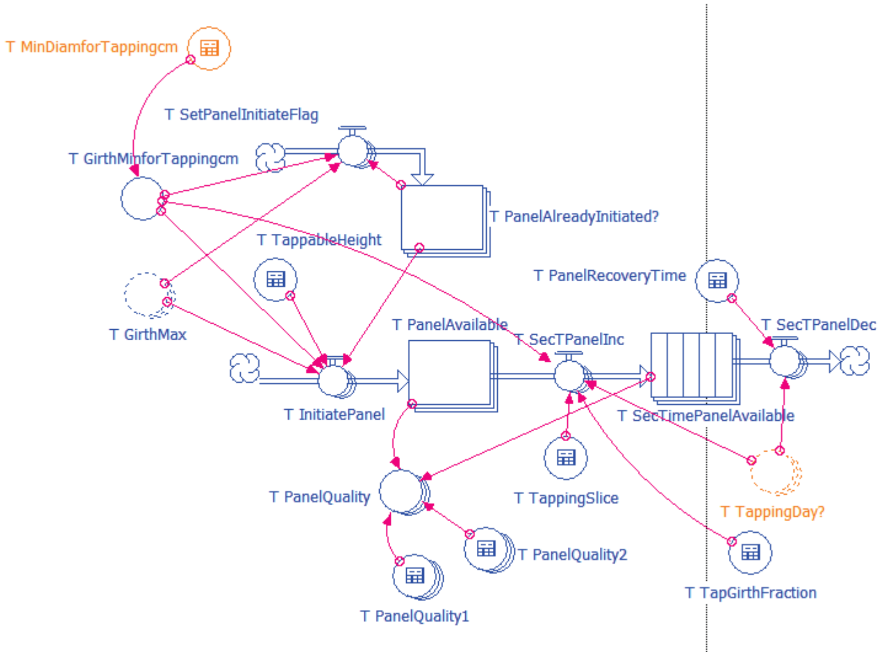


Figure 3.33. Diagram that show dynamic of available tapping panel and its influence factors
The latter ratio is derived in a section of the model that also converts the latex yield per tree to a dry weight of rubber per ha, using the appropriate area scaling factor.

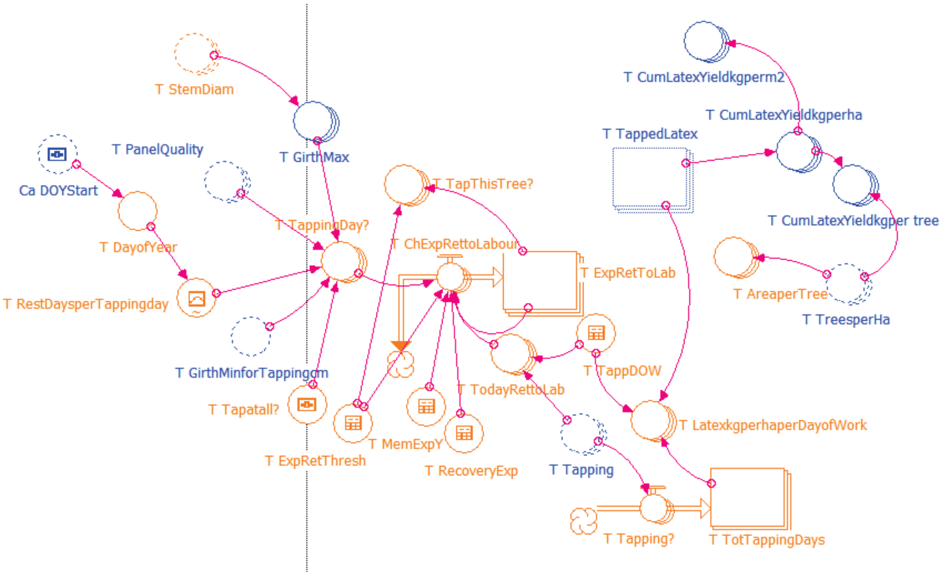


Figure 3.34. Diagram that show influence factors for tapping schedule selected and farmer decisions to tap the tree.

This module has been developed as part of the PhD research of Dr. Yahya Abdul Karim, and was paramaterized by him for rubber clone comparisons in Malaysia.

3.9. Carbon balance

3.9.1. Soil organic matter

Total soil organic matter is supposed to consist of 'metabolic' and 'structural' pools in the recently added organic materials, an 'active' (= microbial biomass), 'slow' and 'passive' pool. This terminology is derived from the Century model. This part of the model was developed in discussions with Dr. Georg Cadisch (Wye College, UK) and Dr. Andy Whitmore (AB-DLO, the Netherlands).

In agro-ecosystems without soil tillage, a distinct litter layer develops where much of the organic inputs decompose with little contact with the mineral soil layers. The dynamics of C and N here can differ substantially from that in the soil layers, as the 'physical protection' mechanisms based on soil texture are absent, and temperature and water dynamics differ. Incorporation of surface litter into the soil can be the result of specific groups of the soil fauna, as well as of mechanical tillage operations. Starting from version 2, WaNuLCAS therefore represents the C, N & P pool dynamics for the litter layer separate from SOM dynamics, using the Century pool descriptions for both (all parameter names MC_... and MN_... refer to the litter layer, names MC2_.. and MN2_... to the SOM pools). The texture, water and (potentially) temperature controls differ between these layers. For N immobilisation the litter layer has limited access to soil layer 1, while all mineralization products arte delivered to layer 1. For the SOM pools, a weighted averaged is made of layer 1...4 for all its relations with soil water and N pools (including immobilization and mineralization). The weighing factors for the soil layers are set at the start of the model (but can be made dynamic if one wants).

An option is introduced to initialize on the basis of the Corg/Cref ratio, where Cref is either derived from a pedotransfer function (Type = 2) or specified by the model user (Type = 3). The relative allocation of Corg to the slow, active and passive pool is driven by the Corg/Cref ratio for Types 2 and 3.

1. for MC_SOMInitType = 1 the user can specify all pool sizes for all zones,
2. for MC_SOMInitType = 2 the user can specify the size of all pools relative to those for a forest soil (Cref) that is calculated from soil texture data,
3. for MC_SOMInitType = 3 the user specifies the Corg and Cref directly, but otherwise follows the procedure of Type 2

Input streams of organic matter from crop residues, tree litterfall, prunings and/or external organic sources supply 'metabolic' and 'structural' pools, by adding all C, N, lignin and polyphenolic contents of all inputs on a given day. Century's distribution equation is then applied to allocate these streams to metabolic and structural litter pools. This represents a 'simple mixing' algorithm, without specific interactions between residues.

Before the Century equations are applied, however, the total polyphenolic content is supposed to immobilize N from the current organic inputs and (if necessary) soil Nmin pool, into the 'slow' pool of C and N. This equation can account for some of the non-linear effects when residues with low and high polyphenolic content are mixed.

Immobilization of mineral N can occur where metabolic and especially structural SOM pools are utilized by microbial biomass to make 'active SOM', with a low C/N ratio and (for structural litter) 'slow SOM'. Modifications were made here to the model (if we understand what the Century handles this situation). The flow of C is driven by the preceding C pool size and the relevant decomposition parameter k. This C flow induces a parallel N flow on the basis of the C/N ratio of the preceding and subsequent SOM pool.

If there is sufficient Nmin in the soil layer, this will be used to meet the 'target' C/N ratio of the subsequent pool. If there is not enough mineral N, however, to (fully) meet this demand the C/N ratio of the subsequent pool will increase. This will have two effects:

1. further transformations of SOM will slow down, and reach a halt where the microbial biomass has a CN ratio of 1.75 times the 'target' value. The value 1.75 was suggested by Dr. Georg Cadisch.
2. the SOM pools remain 'hungry' for mineral N and will re-stock their N content to meet the 'target' whenever mineral N becomes available in the soil again.

These modifications to the Century model are mainly relevant at relatively small time scales (less than the yearly time steps for which Century was designed). The model can now potentially account for the rapid disappearance of mineral N into the soil after fertilizer N additions, while such fertilizer may become available to subsequent crops.
Apart from the freedom to set parameters, a number of options on model structure was built into WaNuLCAS:

The k values driving the SOM-C and SOM-N transformations are a function of clay content and soil temperature as in the Century model, and an additional reduction based on soil water content. For example, for the active pool the k value is calculated as:

$$k = 0.14 * (1 - .75 * Mc\_SiltClay) * Mc\_TempLim * Mc\_TethaLim[Zone] \qquad [76]$$

where the 0.14 and 0.75 are the parameter values for the active pool (other pools use different values but the same reduction factors). Make sure that the value of silt and clay content used should be consistent with the value used in deriving soil hydraulic properties.

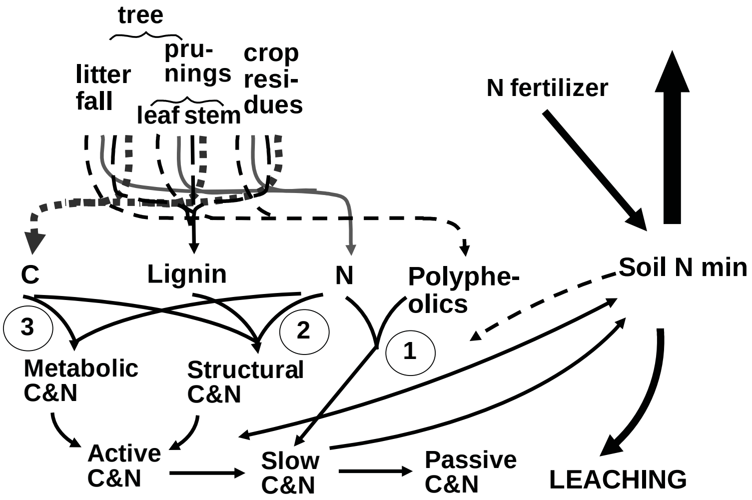


Figure 3.35. Major relationships in N immobilization and N mineralization from organic residues; the basic C and N pools are similar to the Century model, but plant polyphenolics are added as litter quality parameter.

3.9.2. Carbon stocks

An output table is provided which summarizes the carbon balance, similar to the water, nitrogen and phosphorus balance sheets.

On the left hand side it includes all initial carbon stocks in soil, crop and tree (with plant biomass converted into carbon units) and all net daily photosynthesis by crop and tree. On the right hand side it lists all final carbon stocks in soil, crop and tree, all carbon in products removed from the plot and all carbon lost as CO_2 in soil organic matter transformations. Plant respiration is implicit in the net photosysnthesis and thus does not appear on the C balance sheet.

3.10. Management options

3.10.1. Options for strategic and tactic management

The WaNuLCAS model can evaluate a number of farmer management options. These can be grouped in strategic decisions, to be made by a farmer before crops are planted and by a modeler at the start of a simulation and tactic management during a growing season, in response to actual crop performance.

Strategic options include:

- Plot size and tree spacing,
- Choice of tree species as reflected in their functional parameters of canopy shape and branch allocation, root distribution under given soil conditions),
- Cropping cycle: crop types and planting dates.
- Predetermined pruning events
- Pre-determined tree final harvest and/or tree mortality

- Slash-and-burn events, including options to remove part of the wood before the burn,
- Building a fence around the plot

Tactical options represented in the model are:

- Tree pruning based on current tree and crop status,
- Use of fertilizer and organic inputs and their distribution over the zones,
- Crop residue removal,
- Maintaining the fence.

At this stage only two types of plants are considered and thus we imply that there are no weeds. The equations for resource sharing and competition are set up in such a way that the model can be extended to an n-plant interaction and different plants can share a zone in the model, above as well as belowground.

3.10.2. Slash-and-burn events

A number of ‘Slash’ events can be defined in the event calendar, by specifying the S&B_SlashYear and S&B_SlashDOY tables. Slash events transfer all current aboveground biomass in tree, weed or crop pools to the S&B_Necromass pool. This refers to the dryweight, N and P contents of these pools. From the S&B_Necromass a fraction can be transferred daily to the surface litter pool, as set by the S&B_DailyNecromLittTransf parameter, where it will follow century-model based transformations of C, N and P pools. The S&B_Necromass pool will intercept part of any rainfall events, replacing the role played previously by tree and crop biomass, and the subsequent evaporation from the ‘Rain_CanopyWater’ pool will determine the moisture content of the necromass. When this is below a set value (‘S&B_CritWatContent’) the switch ‘S&B_IsSlashDry?’ will be turned on, allowing burn events to take place, otherwise it is turned off.

Burn events are defined by specifying a minimum and maximum number of days after the most recent ‘slash’ event. A fire event will be implemented on the first day in this period that the signal ‘S&B_IsSlashDry?’ is on. During a burn event, the temperature increase at the soil surface is calculated from the necromass + structural part of surface litter, with corrections for their respective moisture contents based on ‘Rain_CanopyWater’ and ‘W_Theta1[Zone]’. Temperature calculations need two parameters: ‘S&B_ FuelLoadFactor’ and ‘S&B_TempWetnessCorr’. The temperature increase in the topsoil is derived from the temperature increase at the soil surface, modified by soil water content of the topsoil.

Burn events can have impacts on a number of pools in the model, either via the temperature at the soil surface or that in the top soil:

- reduction of surface necromass, surface litter and SOM pools, by S&B_NecromassBurnFrac, S&B_SurfLitBurnFrac and S&B_SOMBurnFrac, respectively,
- allocating all C of the burnt necromass to CO_2, and 1 - S&B_NutVolatFrac of its N and P content to mineral nutrients at the soil surface,
- induce a (one-off) transfer from the immobile P fraction in the topsoil via S&B_FirIndPMobiliz
- induce a semi-permanent relative change of the effective P sorption via S&B_

FirImpPSorption; a gradual return to the original P sorption value will be governed by S&B_PsorpRecFrac

- release cations into the topsoil from burnt necromass, leading to an increase of topsoil pH; this change of pH will modify the P sorption properties as well, with the overall effect obtained by multiplying the two factors,
- evaporate all soil water from the topsoil if the temperature exceeds 100oC via S&B_FireWEvap
- modify soil water retention properties via S&B_FireImpactonWatRet, with a gradual return to the original values governed by S&B_WatRetRecFrac.
- induce tree mortality switch S&B_FireTreeMort? if the temperature exceeds the S&B_TreeTempTol[tree]
- induce mortality in the weed seed bank via S&B_FireMortSeedBank

Most of the above impacts is related to temperature via a graphical input; impacts can be set to zero by modifying these graphs.

3.10.3 Tree mortality

Trees can die due to fire (see 3.10.2) or at a set date (T_KillYear and T_KillDOY). Currently, we can kill, replant then kill of any tree on acertain zone up to 3 times on 1 length of simulation.

If Rt_ATType = 2 is used, any remaining root biomass at that time is treated as input to the soil organic matter module.

3.10.4. Weed growth

An option is provided to include weed growth in the simulations, outside of the cropping periods. If the switch C_SimulateWeeds? is set at 1 (in stead of 0), weeds will start growing whenever crops are absent, based on a fraction C_WeedGermFrac of the current seedbank of live weed seeds. The seed bank (dry weight) is initialized at C-WeedSeedBankInit kg m^{-2} for all zones, with nutrient contents based on C_SeedConc. Daily influx of weed seeds from outside of the plot equals C_WeedExtInflux, while a fraction C_DailyWeedSeedDecay is transferred to the litter layer. During fire, additional decay of viable seeds will be accounted for, depending on the temperature on the topsoil.

Growth of the weed biomass follows the rules for crop growth, with a parameter set chosen on the basis of Cq_WeedType (default = 10). The weed can have a perennial or annual growth habit, depending on the value of Cq_SingleCycle? for crop type 10.

3.10.5. Pests and diseases

Leaves, roots, fruits and wood of crops and trees can be eaten by herbivores, rhizovores, frugivores and lignivores, respectively. The user can define a constant daily fraction to be removed from each plant organ types by such events. This is a skeleton on whicg the user can build, e.g. by making the impacts dependent on crop stage and/or the amount of alternative food for the organims involoved. A simple version of a pest population dynamics module is included, that allows pest organisms (nasties) to enter the plot from the surroundings of the simulated area. A fence can be build around the plot and the various categories of pest can either jump the fence or be deterred by the fence if it is in a good enough condition (PD_FenceQ >= 1). Again, this is a skeleton of a module only, and the user who is interested in this type of interactions and lateral flows will have to provide more detail.

3.10.6. Fence

Fence quality is supposed to be related to initial labour time investment according to Q = M * L/(K + L), where M is the maximum quality (PD_FenceFullQuality) and K the amount of labour to reach half of this maximum (PD_HalfFenceTime). To calculate the change in fence quality due to subsequent labour investment, we can first express the current condition in an equivalent time (t = K Q/(M - Q) and then calculate the new quality based on this time t plus the new labour time investment. The change in fence quality due to a new time investment Lcurr becomes:

$$\Delta FenceQuality = Lcurr(M-Q)^2 / (KM + Lcurr(M-Q)) \qquad [67]$$

In WaNuLCAS two options are provided for fence building and maintenance: if PD_FenceMaint? = 1 a certain amount of labour is spent (PD_FenceMUnit * PD_HalfFenceTime) whenever there is a crop on the field (in any of the zones) and the current quality of the fence is below the threshold (PD_FenceQThresh. If PD_FenceMaint? = 0, fence building responds to a calendar of events specified by PDFeceBuildY, PD_FenceBuildDOY and PD_FenceBuildLabSeq (the latter in units relative to PD_HalfFenceTime).

Fence quality decays by a fraction PD_FenceDecK per day. Costs for fence building and maintenance are taken to be proportional to the amount of labour spent, and the P_FenceMatCost[PriceType] value is supposed to be spent when the amount of labour used equals PD_HalfFenceTime.

3.10.7. Tree pruning

For tree pruning the following options are provided:

- **T_PrunY** and **T_PrunDoY** allow the user to specify pruning dates, similar to the cropping calendar. This option may be especially useful if simulations are to be compared to actual data sets. If the user does not want this type of pruning events, the T_PrunY for the first event should be after the simulation run ends.
- **T_PrunPlant?** Determines whether or not the tree will be pruned every time a new crop is planted (0 = not, 1 = yes)
- **T_PrunLimit** specifies a critical total LAI of tree canopy above which trees will be pruned, if and only if there is a crop in one of the zones
- **T_PrunStageLimit** will ensure that no tree pruning is implemented in the later part of the crop (after this stage in crop development), to avoid tree pruning just before crop harvest.
- For each pruning event, the parameter **T_PrunFrac** specifies the fraction of tree canopy biomass removed. This can be specified as constant for every pruning event or changes for every event.
- **T_PrunHarvFrac** specifies the fraction of prunings that is removed (harvested) from the field, e.g. for use as fodder. This can also be specified as constant or dynamic.

3.10.8. Tillage

This option relates to Soil Erosion and transfer of litter to SOM pools. Tilling can be specified from a calendar, or be automatically implemented at X days before planting a new crop.

3.10.9. Timber Harvesting

Timber can be harvested, specified in Excel sheet Tree Management. When timber is harvested all canopy biomass and fruit are removed from plot.   T_WoodHeight will decreased depending on fraction of timber removed.

3.10.10. Grazing

Grazing will affect crop/grass only and 2 types of grazing pressure can occur, field and patch level.

Field-level grazing pressure depends on two factors:
1. stocking rate in standard livestock units as a function of simulation time.
2. daily intake requirement per animal.

Patch-level grazing pressure depends on field-level grazing pressure, relative attractiveness of grass/crop in the patch and total fodder availability in the field. Relative attractiveness of grass is a function of standing biomass, N concentration and growth stage. Input parameters related to this module are:
1. Graphical inputs specifying the attractiveness on the basis of biomass (G_BiomDep), N concentration (G_Ndep) and growth stage of the grass (G_StageDep).
2. A graphical input defining the stocking rate as a function of time (G_StockrateperHa)
3. Daily requirement per standard livestock unit=SLU (G_DayDempDayKg, default value 2.5% per dry weight SLU)
4. Standard live stock unit (G_SLU, default value 450 kg)

The possible output are cumulative biomass grazed, G_GrazedBiomCum(in dry weight) and its nutrient content). For future modifications, we plan to have rule for relating stocking rate to standing biomass as result of actual grazing success. This would reflect farmer decision making in managing the system.

3.11. Model output

3.11.1. General

A number of graphs and tables is provided for viewing output of a WaNuLCAS simulation, but the **STELLA** environment allows a user to interrogate the model for the value of any parameter at any time step desired.

On the ‘Output menu’ one has a choice between viewing graphs of biomass and elements of water and nutrient balance for the system as a whole, or specific by zone. An overview of the balance of inputs and outputs is given for N, P, C, water and money. The 'yields' screen translates the dry weights of the model to the moisture contents conventionally used for agronomic yields (as governed by the .C_AgronYMoistFrac parameter in crop type).

3.11.2. Financial analysis

The WaNuLCAS model can predict the outcome of patch-level performance of agroforestry systems under a range of management choices. In version 2 a simple financial analysis is provided in the form of a Net Present Value calculation. Dr. Thomas P. Tomich and Mr. Suseno Budidarsono (ICRAF SE Asia) advised on the development of this section. The basic equation is:

$$NPV = \sum \frac{-cost + return}{\{1 + DiscountRate/365\}^{Time}} \quad [68]$$

Two types of prices can be used simultaneously, social and private, so as to allow an analysis of the impacts of economic policies and market imperfections on the profitability of the agroforestry system simulated. As we do a daily accounting of costs and returns, no separate category of 'working capital' is needed as one would use for an annual accounting system. Costs and returns included in WaNuLCAS are listed in Table 3.7.

Table 3.7. Costs and returns included in the calculation of net present value in WaNuLCAS.

Costs	Returns
Planting material for crop and tree	Harvested crop yields
N and P fertilizer or pesticides used	Harvested tree products (wood, fruit, latex, prunings used as fodder)
Organic inputs	
Labour for tree planting, management and harvesting	
Labour for crop planting, management and harvesting	
Labour and input costs for field protection (incl. fence building and maintenance)	

3.11.3. Filter functions

Tree and crop roots can exert 'safety-net' or 'filter' functions by intercepting nutrients from various depths of the soil, and thus preventing them from losses by vertical leaching or horizontal lateral flow. The ratio of uptake to (uptake + loss) can be used to indicated the local filter function (Cadisch *et al*. 1997, Rowe *et al*., 1999):

$$N\_LocFF_{ij}[Nutrient] = Upt_{ij}[Nut]/(Upt_{ij}[Nut] + Loss_{ij}[Nut]). \quad [69]$$

$$N\_LocFF_{ij}[Nutrient] = Upt_{ij}[Nut]/(Upt_{ij}[Nut] + Loss_{ij}[Nut]). \quad [70]$$

$$N\_TotFF[Nut] = TotUpt[Nut]/(TotUpt[Nut] + TotLoss[Nut]) \quad [71]$$

where the TotLoss is accounted for at the boundary of the system, ignoring internal transfers within the system. The total filter function by this definition is not equal to the sum (or average) of the local filter functions, as the divisors of the ratio differ. The total filter efficiency can, however, be split into the contributions of each cell:

$$N\_TotFF[Nut] = S_i\ S_j\ N\_TotFF_{ij}[Nut] =$$
$$= \Sigma_i\ \Sigma_j\ Upt_{ij}[Nut]/(UptTot[Nut] + LossTot[Nut]) \qquad \textbf{[72]}$$

The N_TotFFij values can be added up to obtain the total filter function of a certain layer or column. Of particular interest may be the filter function of the bottom layer and that of the lowermost column. A third type of filter function can be defined for the ‘edge’ of the system., i.e. layer 4 + zone 1 (but avoiding a double count of cell 1.4):

$$N\_EdgeFF[Nut] = \Sigma_{k=edg}\ UptEdge_k[Nut]/(UptTotEdge[Nut] + LossTotEdge[Nut]) \qquad \textbf{[73]}$$

This edge filter function can be partitioned in a horizontal (zone 1) N_EdgeFFH[Nut] and vertical (layer 4) N_EdgeFFV[Nut] component, by sharing the uptake from cell 1.4 over the two in proportion to the cumulative loss in horizontal and vertical direction from this cell.

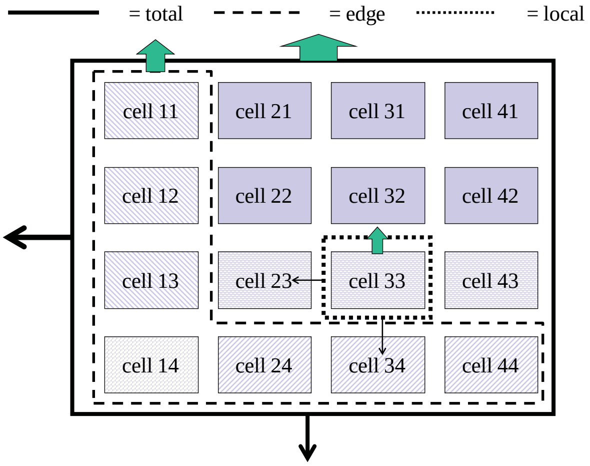


Figure 3.36. Filter functions (or safetynet functions) are defined as uptake/(uptake +loss) at three scales: local (as example here for cell 3.3), edge (uptake from zone1+layer4, net losses from the edge equal net losses from system as a whole) or system as a whole

3.11.4. Number of days plants has growth limitation

We defined this as fraction of days (out of the length of simulation days) tree or crop is limited by water, nitrogen or phosphorous.

Chapter 4

Examples of model applications

We first explore a simulation based on the 'default' parameters of version 3.0 and see how crops, trees and weeds interact and compete for N, P, water and light on soil rich in organic matter but with limited rooting depth due to subsoil acidity.

After that, five examples of model applications (made with version 3.0) are presented, to test the objective that the model can be applied to a wide range of agroforestry research questions.

Results are not compared to specific data sets and no parameter fitting has occurred. Examples are presented for simulation runs of a simple soil-crop system at different N fertilizer regimes, hedgerow intercropping systems at different hedgerow spacing and pruning regime, a test of the safety net function of deep tree roots, lateral interactions in crop-fallow mosaics and a first exploration for parkland systems with a circular geometry across a rainfall gradient and some more examples of WaNuLCAS application on the agroforestry research.

In each example, a list of input parameter changes is provided. These changes are relative to default values. If you have made recent changes in WaNuLCAS.stm and would like to return to default values for a group of parameters, click on undo button (U) at the top of list input device. If you want to reset all parameters to their default values, you can use a "Return to DEFAULT value" button in the "Input" section

4.1. Simulation based on default parameter settings

For a start, the default parameter settings can be used to become familiar with the various types of model output that can be obtained. The default settings simulate an alley cropping system of maize and *Peltophorum dasyrrachis*. Figure 4.1 gives the biomass production results for a ‘default’ run of 2 years duration in which the trees are always pruned before planting a new crop. In the first cropping period there is little difference in crop growth between the three zones. In the first cropping season of year two, crop growth starts to differ significantly between zones and the crop in zone 2 (close to the hedgerow) produces less biomass compared to zones 3 and 4, as it faces more competition in terms of water, nutrient and light. During fallow period the hedgerow trees start develop more biomass until the next cropping season when the hedgerows are pruned; the woody part of the hedgerows is maintained, so overall aboveground tree biomass can gradually reach a higher level.

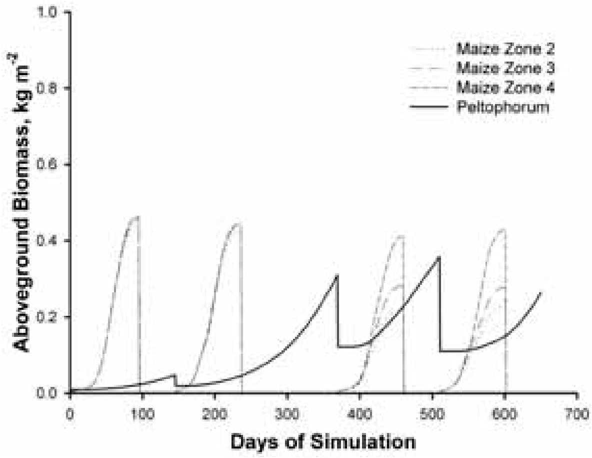


Figure 4.1. Biomass development of crop and tree for a WaNuLCAS simulation using ‘default’ parameter settings

If you click on ‘To View Water Input Output Summary’ you will see results of the water balance. The only inputs of water were due to rainfall directly on the simulated area, as the default slope of 0% stops any Run-On or Lateral Inflow (but not the option of Run-Off). Out of a cumulative rainfall of 5812 mm (i.e. 2606 mm year^{-1}), 79 mm was used to recharge the soil (which was initialised below field capacity), 3723 mm drained from the soil profile, 174 mm became surface run-off, 636 mm evaporated from the soil surface, 146 mm evaporated from interception by crop and tree canopy, 731 mm was transpired by the crop and 324 mm by the tree. The BW_NetBal result of 4.5 10^{-13} indicates that the error in accounting for all inputs and outputs of water is negligible.

The N balance shows that there has been a considerable net mineralization of N during the simulation, with the SOM_N pools decreasing from 247 to 227 g m^{-2}. Neither crop nor tree fixed atmospheric N_2 and no N fertilizer was applied. The stock of mineral N has increased from 1.1 to 1.65 g m^{-2}, while 9.5 g m^{-2} was lost through leaching and 7.6 g m^{-2} was exported with crop harvest products. At the end of the run N the tree biomass was 2.2 g m^{-2} and the error term of the N balance was –5.68 10^{-14}

In the P balance we again see that mineralization of organic P has been the major supply of P to the crop and tree, with the organic P stock decreasing from 57 to 55 g m^{-2}. In contrast to N, however, leaching losses have been very small (0.14 g m^{-2}). The error term of -1.8 10^{-13} again indicates that there are no problems of consistency.

The 'Filter Function' output sector indicates that overall the agroforestry system has been quite effective in capturing the N and P released from the soil organic matter before it leached out of the profile, with an overall filter efficiency of 67 and 98% for N and P, respectively. A substantial part of this overall filter function was located in the 'Edge': filter function horizontally was 17 and 73% for N and P, respectively; filter function vertically was 7 and 2% for N and P, respectively. The local filter efficiency in layer 3 (relative to leaching and lateral flow losses from each cell) clearly decreased from zone 2 to zone 4, with decreasing root length density of the tree. The filter functions are higher for P than they are for N as the lower mobility of P (relative to N) retards the leaching and increases the P residence time, giving more opportunity for uptake; this effect apparently exceeds the impacts on uptake of a larger diffusive resistance.

The C balance shows again the decrease in soil C during the simulation (2679 to 2438 g m^{-2} or 27 to 24 Mg ha^{-1}), while total photosynthesis of the tree is more than half of that by the crop (319 and 536 g m^{-2}, respectively), most of which was lost in respiration. At the end of the two years simulation, 335 g m^{-2} has been exported from the field in crop products, while the current tree biomass is 111 g m^{-2}. The error term of the C balance is negligibly small at 0, while the 'time-averaged C stock' is 2641 g m^{-2} (or 26 Mg ha^{-1}).

The 'Yields' sheet specifies the agronomic yields obtained from the system as a whole. Only the maize crops ('Type 2') are counted, as the trees did not (yet) produce any directly usable products, current tree biomass harvested comes from tree biomass pruned (8 Mg ha^{-1}). The maize grain yield of 0.94 kg m^{-2} or 9.4 Mg ha^{-1} (3.3, 3.1, 2.2 and 2.2 Mg ha^{-1} per crop, respectively) is quite good. During the simulation N, P and water limited crop growth 37, 64 and 0 % of days in the cropping period, and tree growth for 34, 13, and 0 % of the year.

The 'light' output shows crop growth limitation by light capture. The value 0.99 means the growth of the crop was hardly limited by light.

The 'soil balance output' gives result for the amount of soil loss and current topsoil thickness. As the default value for slope 0%, topsoil thickness after two years simulation is the same to the initial value means no soil was lost during the simulation.

4.2. The use of the main switches and changes in crop or tree type

A number of ways exist to further explore the backgrounds of these results and the way limitations by water, N, P and light interact. One method is to inspect the graphs of current limitations in each zone, as provided in the 'Output' section of the model. A second method is to use the main switches on the 'Output' level and try the various combinations of 'no trees', 'no water, N or P' limitations and 'presence of weeds' for the default setting of all other parameters. Figure 4.2 A-K show the tree and crop biomass results for such runs.

Figure 4.2 A-C shows the crop biomass as a result of changing tree species and absence of the tree. The presence of the tree (comparing Fig 4.2.A-B and C) affects crop growth in zones closer to the tree. Using *Peltophorum* (comparing Fig 4.2.A and C) crop growth starts to differ between zones at year 2. Changing the tree type from *Peltophorum* to *Gliricidia* in the Excel sheet 'Tree parameters' (comparing Fig. 4.2.A and B), the impact of tree on crop growth starts earlier, that is on the second crop season of the first year. The decrease of total tree biomass during a cropping period is due to pruning and use of internal reserves in the tree. For *Gliricidia* (Fig. 4.2.B), the total tree biomass decreases during fallow period (no crop). This is due to litter fall caused by drought, as *Gliricidia* is more sensitive to drought than *Peltophorum*.

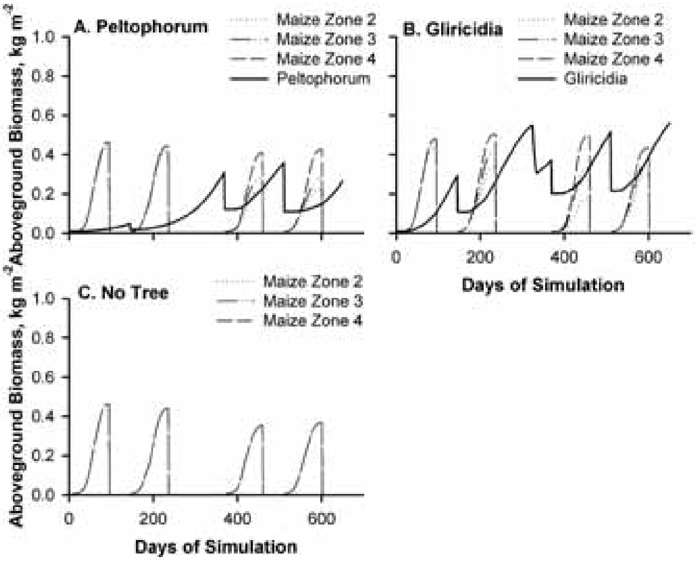


Figure 4.2A...C. Aboveground biomass for a simulation based on default parameters setting in WaNuLCAS using tree type D (=Peltophorum) or E (=Gliricidia) or none (set the slider AF_AnyTrees? to 0)

Figure 4.2 D…G shows the tree and crop growth without water, N or P limitations. Figure 4.2 D…G. indicate that removing the impacts of P limitation has by far the strong impact on overall crop growth. In its normal condition, crop growth during the second year is severely limited by P.

Figure 4.2 H and I show the impact of tree and weed presence in the systems. Current default settings are without weed and with tree. 'Weed growth' can be simulated by specifying the slider AF_SimulateWeeds? in Run and Output section to 1. To set with or without a tree situation, specify the slider AF_SimulateTrees? in Run and Output section to 1 or 0.

The pattern starts to become fairly complex, as the Cr_Biom output in zone 2...4 alternately refers to a crop and weed, while the weed growth in zone 1 is out of phase with the weed growth in zone 2...4. Weeds only grow during the fallow periods (no crop) in zone 2…4. In Figure 4.2.I, a tree is added to this pattern; note that the tree is not pruned when weeds occupy zone 2…4; the tree has some impact on weeds in zone 2, but apparently is not very effective in reducing weed growth, except for those in zone 1.

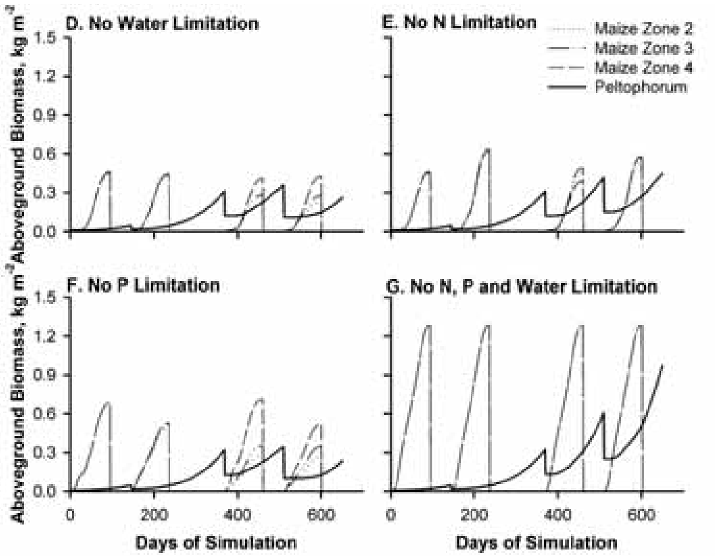


Figure 4.2.D...G. Aboveground biomass for a simulation based on default parameters setting in WaNuLCAS as impact of N, P and water limitation

Figure 4.2 J compare the results for four crop types, each grown in separate zones and each following their own phenological cycle. To obtain this run, return to 'default' settings, set the slider AF_AnyTrees? in 'Run and Output' section to 0 and change the crop types on the 'crop management' sheet in the excel file (Maize in zone 1, Cassava in zone 2, Ground nut in zone 3 and Rice in zone 4). Note that when a tree is added to the systems (set the slider AF_AnyTrees? back to 1), as shown in Figure. 4.2.K, it will be pruned every time prior to planting crop. The presence of the tree significantly affects the biomass of maize that grows closer to the tree.

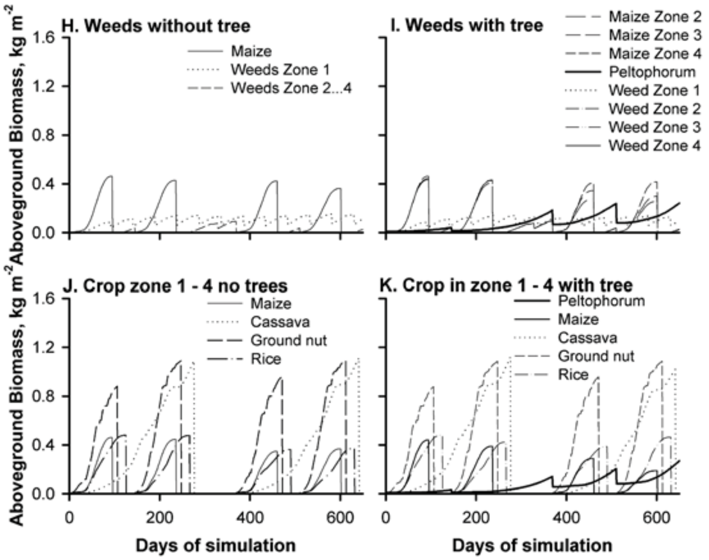


Figure 4.2 H...K. Aboveground biomass for the simple modification (less than 5 mouse clicks) of the default parameter setting in WaNuLCAS 3.0; for explanation see text

4.3. Crop-only controls with N and P fertilizer

We will normally want to compare agroforestry options with a crop only and/or tree only run for the same soil and climate. As an example we use data for maize growth in Lampung (Indonesia) as inspiration for the default case. On flat land, in the absence of a tree, there is no interaction between the crop zones.

So, we can simultaneously make runs for four N fertilizer regimes (0 in zone 1, 60 in zone 2, 90 in zone 3 and 120 in zone 4, kg N ha^{-1} crop^{-1}), by specifying Ca_FertApply?[N] as 1. The amount of N fertilizer equals to 0, 3.5, 4.5 and 6 g m^{-2} that applied twice, half at planting time and half at a month after planting time. For simplicity, we used the same amounts for P fertilizer by specifying Ca_FertApply?[P] as 1. It is applied once at planting time. Figure. 4.3 the simulation beside run at the different of fertilizer application also knows the impact of reducing 50% of soil organic matter content by reducing Mn_InitAct, Mn_InitPass and Mn_InitSlw 50% (see table 4.1 for details of changes from the default parameter setting).

Table 4.1. Input parameter modifications from default to generate example 4.3.

Parameter		Input Section (Link Location in Excel)
INPUT	New Value	
AF_AnyTrees?	0	Run and Output Section
Ca_FertOrExtOrgAppYear	0, 0, 0, 1, 1, 1, 1, 1, 1, 2, 2,2	(Crop management/Fertilizer and organic input schedule)
Ca_FertOrExtOrgAppDoY	305, 306, 335, 81, 82, 111, 305, 306, 335, 81, 82, 111	(Crop management/Fertilizer and organic input schedule)
Ca_FertApply?[N] Ca_FertApply?[P]	1, 0, 1, 1, 0, 1, 1, 0, 1, 1, 0, 1 0, 1, 0, 0, 1, 0, 0, 1, 0, 0, 1	(Crop management/Fertilizer and organic input schedule)
Ca_FertOrExtOrgAmount[Zn1…4] N1[Zn1,2,3,4] N2[Zn1,2,3,4]	 0,30,45,60 0,30,45,60	(Crop management/Fertilizer and organic input schedule)
Ca_FertOrExtOrgAmount[Zn1…4] P[Zn2,3,4]	 0,60,90,120	(Crop management/Fertilizer and organic input schedule)
Mn2_InitAct[Zn1…4]	0.0455	Soil Organic Matter/Initial C & N in SOM Pool
Mn2_InitSlw[Zn1…4]	0.505	Soil Organic Matter/Initial C & N in SOM Pool
Mn2_InitPass[Zn1…4]	0.364	Soil Organic Matter/Initial C & N in SOM Pool

The simulation (Figure. 4.3) was extended to two years, with four consecutive crops of maize. For unfertilised plots with default soil organic matter, crop biomass development started with a good initial crop biomass (with a total biomass of over nearly 0.5 kg m^{-2} (= 5 Mg ha^{-1}), but the biomass declined to 20% of the first year's value in year 2. By reducing 50% of soil organic matter, crop biomass declined to 30% of default value of soil organic matter.

By applying different amount of fertilizer for N and P, the results show that the higher fertilizer, the higher crop biomass. Reducing 50% of soil organic matters does not show significant different on the crop biomass when N and P fertilizer was applied together. Response of the reducing soil organic matter on crop biomass is obtained when only P fertilizer was applied.

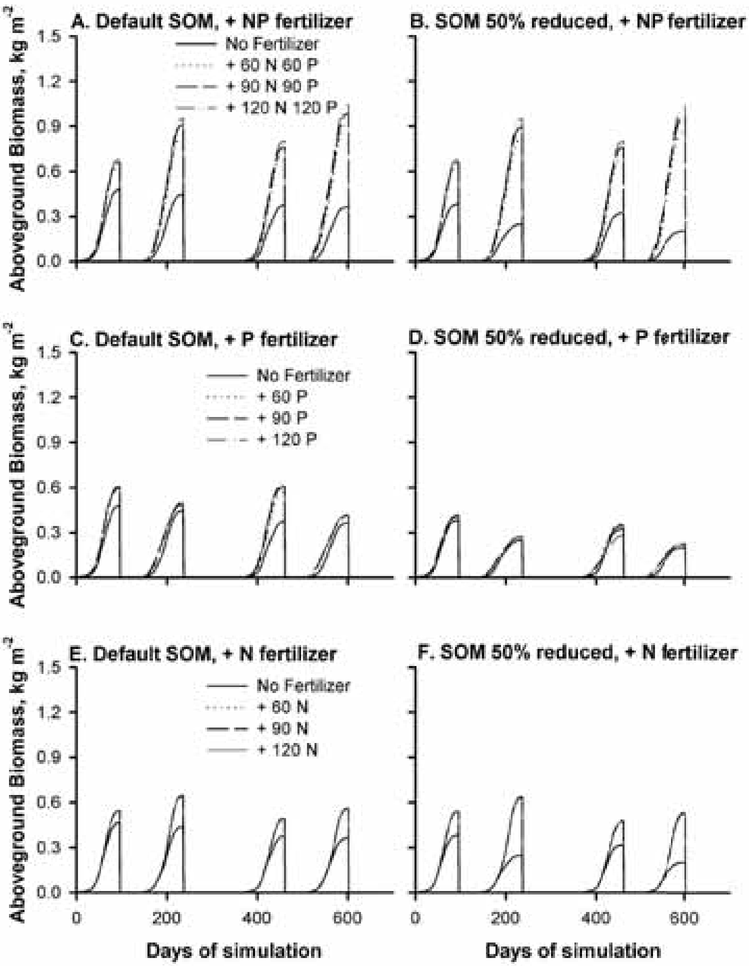


Figure 4.3. A…F. Simulated crop development (total aboveground biomass) for maize with a Lampung climate and default parameters setting (for changes in parameter settings from the default values, see Table 4.1), with or without N fertilizer (at 60, 90 or 120 kg N ha^{-1} $crop^{-1}$, with split application (50% at planting, 50% at 30 days later). We also used the same amounts for P fertilizer; it is applied once at planting time. The simulation also knows the impact of reducing 50% of soil organic matter content.

4.4. Hedgerow intercropping: pruning regime and hedgerow spacing

Based on different tree characteristics (‘P’ and ‘G’ in Figure 4.4), the model predicts different pruning frequencies to be applied (one per crop for P and two to three times per crop for G) by making modifications from the default settings as indicated in Table 4.2. The ‘P trees’ have some characteristics in common with *Peltophorum* as we know that in Lampung experiments while the ‘G-tree’ simulates *Gliricidia* (Van Noordwijk, 1996a). The simulations presented here were made with version 3.0 as a first approximation of long-term hedgerow intercropping experiments in Lampung (Indonesia); details of the experiments that form the inspiration for these simulations can be found in Van Noordwijk *et al*. (1998a).

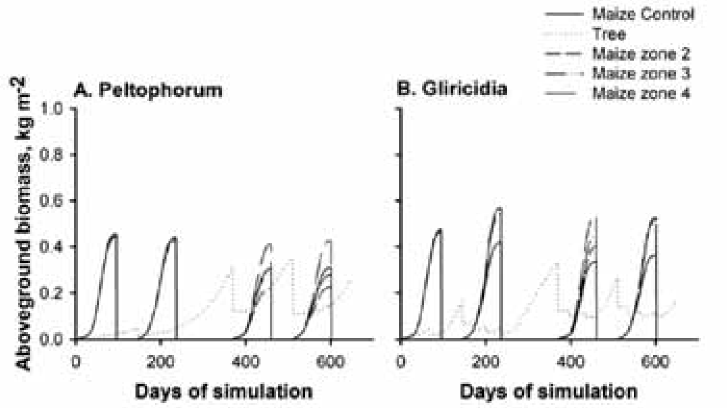


Figure 4.4. Model predictions with WaNuLCAS of development of hedgerow tree canopy and crop biomass (on a whole field basis) over four cropping seasons in two years, for three crop zones (2, 3 and 4) within the alleys (the P and G trees approximate *Peltophorum* and *Gliricidia*, respectively, as used in experiments in Lampung (Indonesia); van Noordwijk *et al*., 1998a); zones 2, 3 and 4 are 1 m wide each; soil type, rainfall pattern and potential maize production inputs were derived form the Lampung site.

The WaNuLCAS model can also predict crop yields in different strips (zones) within the alleys in a hedgerow intercropping system, by making modifications from the default settings as indicated in Table 4.3. The simulations presented here were made with version 3.0 as a first approximation of long-term hedgerow intercropping experiments in Lampung (Indonesia); details of the experiments that form the inspiration for these simulations can be found in Van Noordwijk *et al*. (1998a).

Compared to the maize series of Figure 4.1 and 4.2 which we include as ‘control’, the P trees can partly alleviate the yield decline over time, while the G trees the second crop in each year produces more biomass than the first crop. Averaged over four crops and expressed on a whole-field basis, predicted crop yields for the P hedgerow intercropping system are similar to this control crop while for the G hedgerow intercropping system are slightly higher than this control crop. Hedgerow intercropping will clearly give increased crop growth in zone 4, where the positive effects of mulch are felt, without much shading.

The overall trend in crop yields is negative for P trees and less so for G trees, as the P system is gradually depleting its N stocks, in the absence of atmospheric N_2 fixation in P trees or maize. In the long term field experiments in Lampung crop yields for the control indeed declined rapidly, but no such yield decline was recorded for the treatments resembling P trees.

Table 4.2. Input parameter modifications to generate example 4.4

Parameter		Input /Output Section location
INPUT	New Value	
T_PrunLimit	0.1	Management/Pruning Events

Table 4.3. Input parameter modifications to generate example 4.5.

Parameter I		Input /Output Section location
INPUT	New Value	
Same settings as above with different AF_ZoneTot		Agroforestry zone
AF_ZoneTot	4, 8, 16, 32	
AF_Zone[Zn1]	0.5, 0.5, 0.5, 0.5	
AF_Zone[Zn2]	1, 1, 1, 1	
AF_Zone[Zn3]	1, 1, 1, 1	
AF_Zone[Zn4]	1.5, 5.5, 13.5, 29.5	
T_PrunLimit	0.1, 0.3	Management/Pruning Events

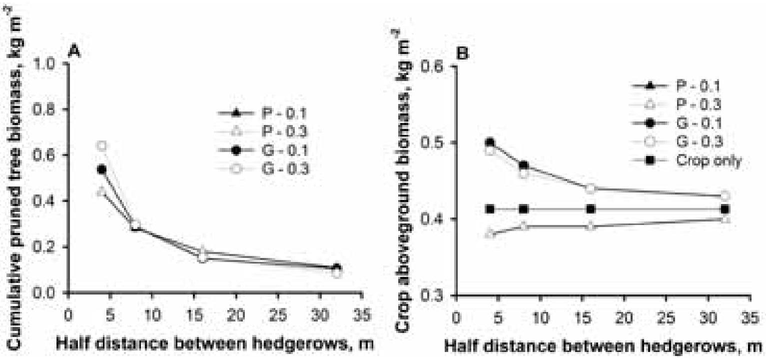


Figure 4.5. Predicted effect on cumulative pruned tree biomass (A) average crop biomass of four cropping seasons (B) if the distance between two hedgerows is gradually increased; results are given for P and G trees (compare Fig. 4.2 and two values of the 'prune limit', i.e. the hedgerow canopy biomass at which hedgerows are pruned back (For details see Table 4.3); and control refers to a whole field planted with crops

The G parameterisation (wider canopy shape, lower LAI within the canopy, shallower roots, N fixation) leads to crop yields that are substantially above the control yields due to biomass pruned from Gliricidia higher than Peltophorum. From the third crop onwards, however yields in zone 3 as well as 2 will be higher than those in the control. In the longer run hedgerow intercropping with G trees is predicted to lead to substantial gains over the pure crop control.

If the distance between hedgerows is gradually increased (Fig. 4.5), the various positive and negative effects on crop yield result in a rather complex overall response. The cumulative pruned biomass clearly decreases with increased hedgerow spacing, but differs remarkably little between the two values of the prune limit: the higher frequency of pruning at a low prune limit compensates for the smaller biomass per pruning event. Crop biomass with the G tree tends to be decrease with increasing of the distance between hedgerows but still above the control value while with the P tree crop biomass slightly increase although below the control value.

The P trees with different prune limit does not give significant different on the crop biomass, while the G tree with high prune limit (G = 0.3) crop biomass lower than G tree with lower prune limit (G = 0.1).

In contrast to Figure. 4.2, the results of Figure. 4.5 can not be compared with any existing experiments we know of, as hedgerow spacing has seldom been systematically evaluated in hedgerow inter cropping experiments. The pattern predicted here is more complex at wider hedgerow spacing than the simple 'shade and mulch' model of Van Noordwijk (1996b), which did not consider spatially zone effects (which matter especially at wider spacing).

4.5. Tree fallow - crop rotations

The WaNuLCAS model can also be parameterised for simulating crop yields on small farms where part of the plot is currently under a tree fallow (such as the *Sesbania* fallows currently tested in Southern Africa), and other parts are cropped. The crop-fallow mosaic will not be drastically different from a hedgerow-intercropping situation: the spacing between hedgerows is wider, broader zones of tree growth replace hedgerows and the pruning regime is modified, but otherwise the processes of tree-soil-crop interactions are the same.

The simulations presented here were made with version 3.0 based on default setting with not applying fertilizer. Parameters modification needed to simulate the system are shown in Table 4.4. The simulation requires two runs in which output from the 1st run becomes input for the 2nd run. Notice also that output values from the tree zone should become the input values in crop zone and vice versa. The soil nutrient content of the tree zone can be directly used as input for crop zones while we need to start the tree zone with the weighted average of output from crop zones. Here is an example of how to do that for initial N in 1st soil layer.

For the tree zone:
N_Init1[Zn1] = (AF_Zone[Zn2]*N_Soil1[Zn2]+AF_Zone[Zn3]*N_Soil1[Zn3]+F_Zone[Zn4]*N_Soil1[Zn4])/(AF_Zone[Zn2]+ AF_Zone[Zn3]+ AF_Zone[Zn4])

For the crop zone:
N_Init1[Zn2] = N_Init1[Zn3] = N_Init1[Zn4] = N_Soil1[Zn1]
The soil organic matter pools increased is size during a fallow period (in the model mainly by litter fall, which is supposed to be mixed through the upper soil layer by abundant faunal activity) and depleted during cropping. The model predicts that there will be substantial 'border effects' of the fallow on neighbouring crop land, not only caused by shading (zone 2) but also by root competition (zone 3).

The WaNuLCAS model may offer the first opportunity to consider crop-fallow mosaics as a coherent system, in stead on only regarding the sequential effects on plots that are supposed to be spatially isolated. The models may stimulate a renewed research attention on border effects in crop-fallow experiments, as no published data exist on the topic. Substantial border effects of teak (*Tectona*) stands in Java (Indonesia) were described in the 1930's (publications of Coster, reviewed in Van Noordwijk *et al*., 1996), and these were larger than what WaNuLCAS predicted for the parameters in Figure. 4.5. Unfortunately, no tree root length densities are known for these (or similar) teak stands. Border effects in crop-fallow mosaics make that the overall effect will depend on the scale (absolute plot size) and not only on the crop: fallow ratio.

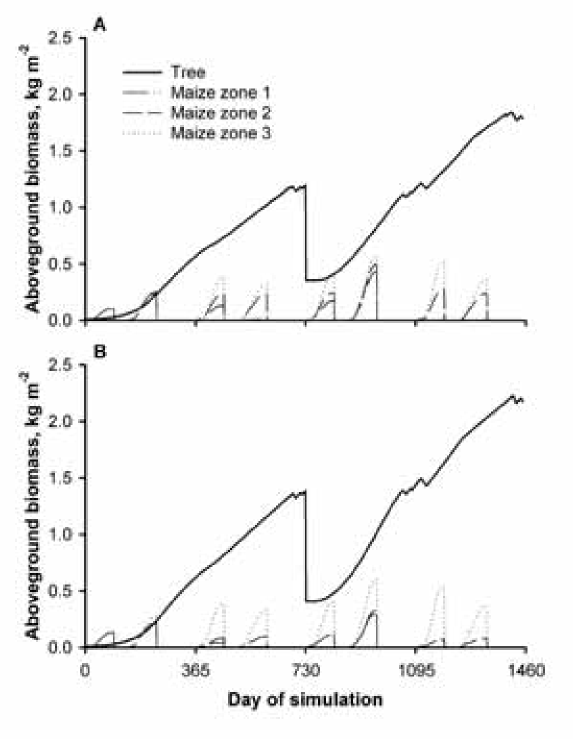


Figure 4.6. Predicted development of a tree fallow vegetation as well as the simultaneous yield of crops with increasing distance to this fallow plot, over two cycles of a two year fallow and 2 years of cropping (4 crops/ cycle); A. tree root length density decreases by a factor 0.6 from zone 1 to zone 2 and again from zone 2 to zone 3; no tree roots in zone 4; B. Tree root length density in zone 2 and 3 is equal to that in zone 1, but there are no tree roots in zone 4

Table 4.4. Input parameter modifications from default to generate example 4.6 and output parameters to retain.

Parameter for 1st run		**Location on WaNuLCAS Input/ Output Section**
INPUT	New Value	
AF_Zone[Zn1] AF_Zone[Zn2] AF_Zone[Zn3]	10 2 3	Agroforestry zone
AF_ZoneTot	20	Agroforestry Zone
Ca_PlantYear[Zn2…4]	0, 1, 1, 2, 2, 3, 3, 4	Crop Management
Ca_PlantDOY[Zn2…4]	304, 80, 304, 80, 304, 80, 304, 80	Crop Management
T_CanHMax	5	Tree Library/Canopy
T_CanWidthMax	12	Tree Library/Canopy
T_PrunPlant?	0	Management/Pruning Event
T_PrunYear	2	Tree Management
T_PrunDOY	300	Tree Management
T_PrunFracD	0.7	Tree Management
Ca_FertOrExtOrgAppYear	100	Crop Management
	Graph A	**Graph B**
Rt_TLrvL1[Zn1…4]	4, 1.6, 0.64, 0	4, 4, 4, 0
Rt_TLrvL2[Zn1…4]	1, 0.4, 0.16, 0	1, 1, 1, 0
Rt_TLrvL3[Zn1…4]	0.5, 0.2, 0.08, 0	0.5, 0.5, 0.5, 0
Rt_TLrvL4[Zn1…4]	0.1, 0.04, 0.016, 0	0.1, 0.1, 0.1, 0
OUTPUT	**Remarks**	
Mn_Act[Zone]	Use Values at the end of run as initial values for the 2nd run	
Mn_Slw[Zone]		
Mn_Pass[Zone]		
Mn_Struc[Zone]		
Mn_Metab[Zone]		
Mn2_Act[Zone]		
Mn2_Slw[Zone]		
Mn2_Pass[Zone]		
Mn2_Struc[Zone]		
Mn2_Metab[Zone]		
W_Thetai[Zone]/ W_FieldCapi[Zone]		
N_Soili[SlNut,Zone]		

Parameter for 2nd run		**Location on WaNuLCAS Input/ Output Section**
INPUT	New Value	
Same setting as 1st run with additional below		
AF_Zone[Zn1]	5	Agroforestry Zone
AF_Zone[Zn2]	3	
AF_Zone[Zn3]	2	
AF_ZoneTot	20	Agroforestry Zone
Ca_PlantYear[Zn1…3]	0, 1, 1, 2, 2, 3, 3, 4	Crop Management
Ca_PlantDOY[Zn1…3]	304, 80, 304, 80, 304, 80, 304, 80	Crop Management
Mn_Act[Zone]	Use Values resulted from 1st run. Make sure result from crop zones become input from tree zone and vice versa (see explanation in text)	
Mn_Slw[Zone]		
Mn_Pass[Zone]		
Mn_Struc[Zone]		
Mn_Metab[Zone]		
Mn2_Act[Zone]		
Mn2_Slw[Zone]		
Mn2_Pass[Zone]		
Mn2_Struc[Zone]		
Mn2_Metab[Zone]		
W_Thetai[Zone]/ W_FieldCapi[Zone]		
N_Soili[SINut,Zone]		
OUTPUT		
T_Biom		Table 1 page 1
C_Biom[Zn1…3]		

4.6. Contour hedgerows on sloping land

Figure 4.7B gives initial results for a contour hedgerow system on sloping land, cumulated over four crops. The simulations presented here were made with version 1.1. Model comparisons were made to separate the terms of the general tree-soil-crop interaction equation (Chapter 1), but adding two effects of slope: 1. Topsoil can be redistributed from the upper to the lower part of the alley, forming a terrace, but exposing crops in the upper alley to subsoil with a lower organic matter content, 2. Water will be re-distributed by run-off in some zones and run-on in others. If we follow the lines in the Figure from left to right, we see that the effect of not growing crops on the space reserved for hedgerows is negative, but that the uneven water infiltration can make up for the yield loss in the humid series (it reduces N leaching from the crop zone). Considering a regularly pruned hedgerow on the contour instead of a bare strip has a moderate positive effect on crop yields, but terrace formation has a negative effect on yields. For the sub-humid series all effects are weak, and no treatment combination can make up for the space lost to make the contour strip. The results per crop zone (Figure 4.7C and D) contain some surprises, as they show a range of patterns between crops: for some crops the middle of the alleys gives the highest yield, for others the lower alley, or even the upper alley. Although all types of patterns can be observed in real-world experiments, it is surprising that the balance of positive and negative interactions can, apparently, change so easily in the complexity of the WaNuLCAS model. Stride for prominence. Further model validation is necessary before any soil, climate, tree and crop specific model predictions should be seen as more than 'interesting hypotheses'

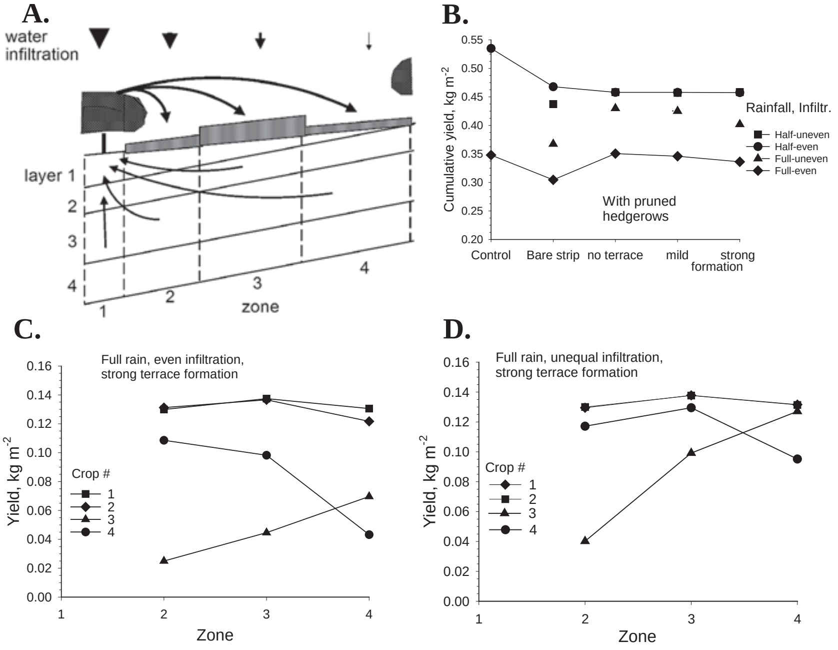


Figure 4.7. Calculations with the WaNuLCAS model (Van Noordwijk and Lusiana, 1999) of crop yield in a contour hedgerow system on sloping land; A. Model scheme for applications on sloping land; B. Cumulative yield over four crops (2 years) for a humid (3 000 mm/year) and sub-humid (1 500 mm/year) climate, with and without uneven infiltration of rainfall over the respective zones; C. and D. results per crop and zone.

4.7. Tree-soil-crop interactions across a rainfall gradient

To further explore the sensitivity of the model a series of calculations was made for an agroforestry system with scattered trees and crops growing on all land except for a circle directly around each tree (Figure 4.8).

For these runs the soil profile consisted of four layers (5, 15, 50 and 30 cm thick, respectively) and had a sandy texture (61% sand, 11% silt, 28% clay) and a bulk density of 1.3 Mg m^{-3}

and thus had a rather low water holding capacity according to the pedotransfer function. Calculations were made for five climate zones, based on random daily rain events with a set monthly average and daily rainfall probability of about 20%. The five climates consisted of:

- annual average 240 mm (1 month of 30 mm, followed by 3 months of 60 mm and 1 month of 30 mm; in practice the average was 285 mm for the runs presented here),
- annual average 450 mm (1 month of 75, followed by 3 months of 100 and 1 month of 75 mm; in practice the average was 525 mm)
- annual average 1000 mm (1 month of 125, followed by 5 months of 150 and 1 month of 75 mm; in practice the average was 937 mm)
- annual average 1500 mm (10 months of 150 mm; in practice the average was 1645 mm)
- annual average 2400 mm (12 months of 200 mm; in practice the average was 2285 mm).

As the same starting value was used for the random generator, all runs for different agroforestry systems in a given climate were made with the same daily rainfall pattern. The simulation run was 2 years, and two crops were grown per year for the 1500 and 2400-mm rainfall zone. Simulations for pure crops (covering the whole field) were compared with those of trees only (unrestricted tree growth) or agroforestry systems where trees occupied the inner circle and crops the remainder of the land. The trees were pruned at sowing time for each crop, and a second time during the crop if their biomass exceeded a set value of 0.2 kg m^{-2} (averaged over the whole field). For comparison a set of simulations was included where the tree was pruned in the same way as in the agroforestry system, but where no crop was grown. Four variants were considered for the agroforestry system, indicated by 'narrow', 'medium', 'broad' and 'very broad' tree canopies with a crown diameter of 1, 2, 3 or 4 quarts of the diameter of the whole system. Note that all zoning is relative to tree size and no absolute distances have to be specified. Tree root length density was 2, 1.5, 0.6 and 0.2 cm cm^3 for the four depth layers directly under the tree, respectively, and 0.6, 0.36, 0 times that value in the three other zones, respectively; thus tree roots were confined to a circle of 3/4 the total diameter. The tree was able to derive 40% of its daily N demand by atmospheric nitrogen fixation and tree N could be transferred to the crop via litter fall and tree prunings, based on a gradual N mineralization. The crop was supposed to have a 98-day duration and a rather shallow root system, with a harvest index under non limiting conditions of 41%. No N fertilizer was used.

From the simulation results using WaNuLCAS, we focus here on grain production (actual harvest index was between 36 and 41%), stem wood production for the tree (treating crop residues, litter fall, pruning and current tree canopy as intermediate components of the system). The simulation involved a gradual shift from water to nitrogen as the major factor limiting crop production. At high rainfall the total N the first crop in the pure crop control effectively exhausted supply in the soil and the three following crop yields were low. Under these conditions the agroforestry system could increase crop yield (by up to 8%), by supplying at least some N for the later crops, thus compensating for the area without a crop and competition effects on crop growth. The medium tree canopy shape (2/4) gave the highest crop yield of all agroforestry systems in the three wettest climates. For the simulations at 450 and 240 mm rainfall, crop yields were reduced in agroforestry by 11 and 35% respectively, as competition for water dominated over positive effects on N supply; at 450 mm the four agroforestry systems gave equal grain yields, while at the 240 mm run, the narrow tree morphology was best. In contrast to grain yield, wood production was always higher in the pure tree system than in the agroforestry system. The narrow tree morphology produced more wood, as it invested less resources in a leaf + fine branch canopy.

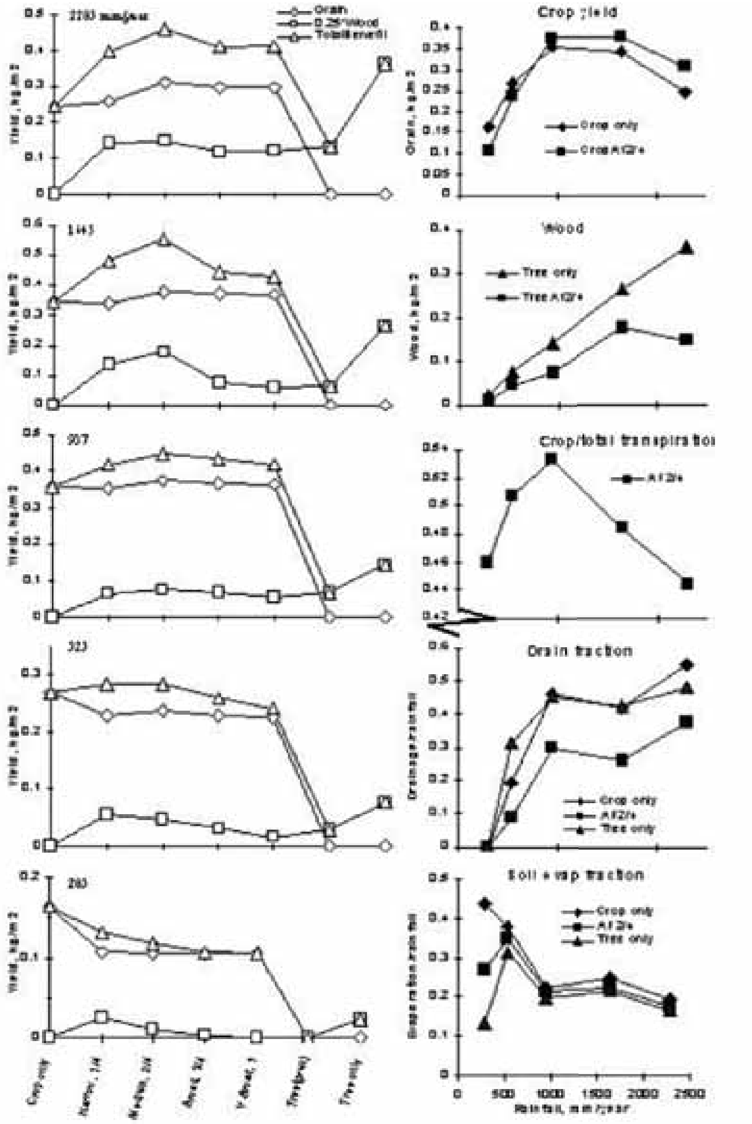


Figure 4.8. Calculations with the WaNuLCAS model of grain and wood production and water use for a range of annual rainfall conditions in an agroforestry system with isolated trees which are pruned when a crop is sown, resembling an early stage of a parkland system; production is accumulated over 2 years, involving 4 (at 2285 and 1645 mm/year) or 2 crops of 98 days duration, on a sandy soil with limited N mineralization from soil organic matter (for main parameter settings see text).

Total yield for the agroforestry system can be calculated if the value of wood can be expressed relative to that of grain. In Figure. 4.7 a 1:4 ratio is used. In the driest simulations there is agroforestry system will reduce total yield, while the curve for the 450 mm zone is nearly flat (and a slightly higher or lower relative value of wood (or other tree products) could shift the balance). For the three wettest climates the positive effects of agroforestry on grain yield are accompanied by additional wood production and agroforestry is superior, unless the relative value of wood is at least 50% higher then we assumed here. The additional production of agroforestry is based on a more complete use of water: the fraction of rainfall draining from the profile is substantially (about 15 20% of rainfall) reduced by the tree crop combination, while model results for soil evaporation losses are intermediate between pure crop and pure tree systems

The share of the crop in total transpiration was always around 50% and peaked in the 1000 mm rainfall situation. Crop water use efficiency was highest at the driest site, as N limitations reduced it in wetter zones. For the tree water use efficiency was not affected by climate as its N fixation was not limited by drought.

As a whole, model calculations may present a reasonable correspondence with real world options, although no experimental data sets exist on the same agroforestry system at the same soil but widely differing rainfall conditions. Any of the effects mentioned here would vary with parameters such as soil depth, soil texture, tree canopy characteristics and rooting pattern or crop root length density, but the basic pattern of response to climate zones would remain determined by overall resource availability. Model results agree with conclusions about the perspective of simultaneous agroforestry systems from experimental evidence (Rao *et al*., 1997; Breman and Kessler, 1997). Mobbs *et al*. (1998) and Cannell *et al*. (1998) came to similar conclusions on the basis of the HYPAR model, which gives a more detailed treatment of aboveground processes and a similar, but less elaborate treatment belowground.

4.8. Model parameter sensitivity for P uptake

WaNuLCAS model was used to explore the effect of root density and presence of mychorriza on phosphorous uptake in agroforestry systems (van Noordwijk, *et al*., 1999).

The predicted P uptake for both tree and crop (Figure. 4.9A and B) respond to changes in root length density (L_{rv}) and mycorrhizal parameters and initial soil P content as one might have expected, with mildly negative responses to increased effective root length density by the other partner (tree or crop). The model's sensitivity indicates that reasonable estimates of effective root length density will be essential for a 'process-based' model. When rhizosphere modification is included (Figure. 4.9C and D), the results point to a clear effect of the synlocation parameter in deciding whether the net effect for the crop of trees with P mobilizing properties will be positive or negative.

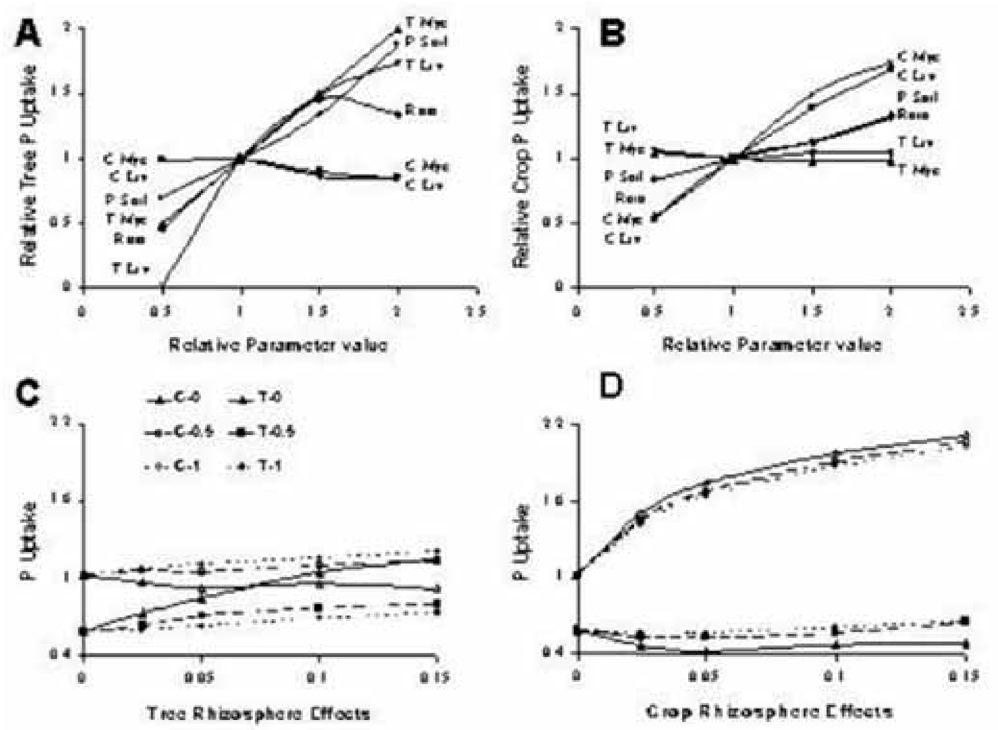


Figure 4.9. Preliminary calculations with the WaNuLCAS model after incorporating a P balance. A and B Sensitivity of predicted P uptake by tree (A (and crop (B) to changes in parameters for root length density T_Lrv and C_Lrv, respectively), mycorrhiza (C_Myc and T_Myc), soil P content (P_Soil) and rainfall. C and D. Effect on P uptake by tree (T) and crop (C) of rhizosphere modification by the tree (C) and crop (D), depending on the synlocation parameter (0 = only plant modifying rhizosphere benefits, 1 = benefits shared on basis of root length density).

4.9. Hedgerow intercropping: safety-net function of tree roots

The WaNuLCAS model can be used to estimate the tree root length density in the subsoil required for efficient functioning of a safety net. A practical definition of the safety net efficiency is the tree N uptake from the soil layers considered, as fraction of total output from this layer by leaching plus uptake. An additional output variable had to be created to capture this parameter.

WaNuLCAS calculations (Cadisch *et al*. 1997) (using version 1.1) where tree root length density in the subsoil was varied over the 0 - 2 cm cm^{-3} range indicated that about 25% of the N leaching below the crop roots can not be recovered (for the soil, climate and tree parameters used) by hedgerow tree roots as it occurs at times that the tree have no current unsatisfied N demand. A nearly linear increase was predicted in safety net efficiency (tree N uptake from the soil layers considered, as fraction of total output from this layer by leaching + uptake) between a tree root length density of 0 and 1 cm cm^{-3}. The model thus predicts that under conditions of continuous leaching a substantially higher tree root length density is needed than what would be adequate for near complete N uptake without a rainfall excess (Van Noordwijk, 1989; De Willigen and Van Noordwijk, 1987). Further data from trials in Lampung (Rowe *et al*., 1999), are in line with this model.

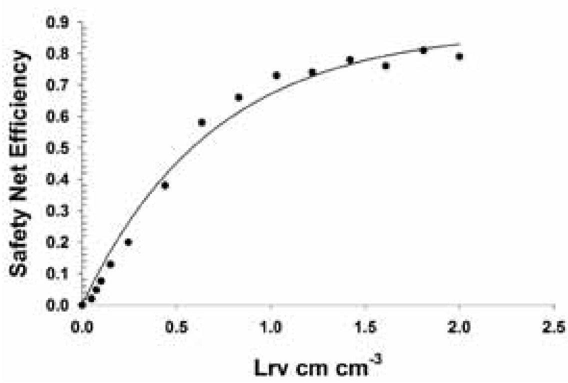


Figure 4.10. Use of the WaNuLCAS model to estimate the tree root length density in the subsoil required for efficient functioning of a 'safety net' (modified from) Cadisch *et al*. (1997); model runs were made with an N adsorption constant Ka of 0.2, reflecting a nitrate-dominated situation as can be expected at high soil pH values.

4.10. Water and nutrient use efficiency in agroforestry systems

Farming systems purely based on annual food crops during and directly after deforestation generally lead to degradation of soil. Establishment of timber and/or fruit trees in cropped fields is feasible and offers better prospects in term of its sustainability. The efficiency of water and nutrient use in agroforestry systems can be used as an indicator of systems sustainability. In this study WaNuLCAS was used to assess the water and nutrient use efficiency in three alley cropping systems (Suprayogo,*et al*., 2002) The crop component is maize and the tree components are: *Paraserianthes falcataria, Hevea braziliensis* and *Swietenia mahagony*.

In this study water use efficiency is defined as: E_{water} (%) = $(T_c + T_t)/R * 100$, where:
E_{water} = water use efficiency,
T_c = crop transpiration,
T_t = tree transpiration
R = amount of rainfall.

Nutrient use efficiency is defined as: $E_{Nutrient}$ (%) = $(N_c + N_t)/(N_{Leach} + N_c + N_t) * 100$, where:
N_t = tree nutrient uptake
N_c = crop nutrient uptake
NL_{each} = amount of nutrient leached

Result shows that water use efficiency in tree based systems tend to increase with increasing age of the tree (Figure 4.11). *Paraserianthes*-maize is the systems with highest water use efficiency while Hevea-maize is the systems with lowest water use efficiency. Presence of trees in the system also reduced runoff and increased supply to ground water stores.

N-use efficiency in tree-based systems also tends to increase with increasing age of the tree (Figure 4.12). *Mahogany* – maize is the systems with highest N-use efficiency while Paraserianthes-maize is the systems with lowest N-use efficiency. The use of N fertilizer caused the N-use efficiency to decrease since N leaching becomes higher. On the other hand, P-use efficiency tends to decrease with increasing age of the tree. This is because P is an immobile nutrient that stimulates accumulation of P in the soil producing low P leaching.

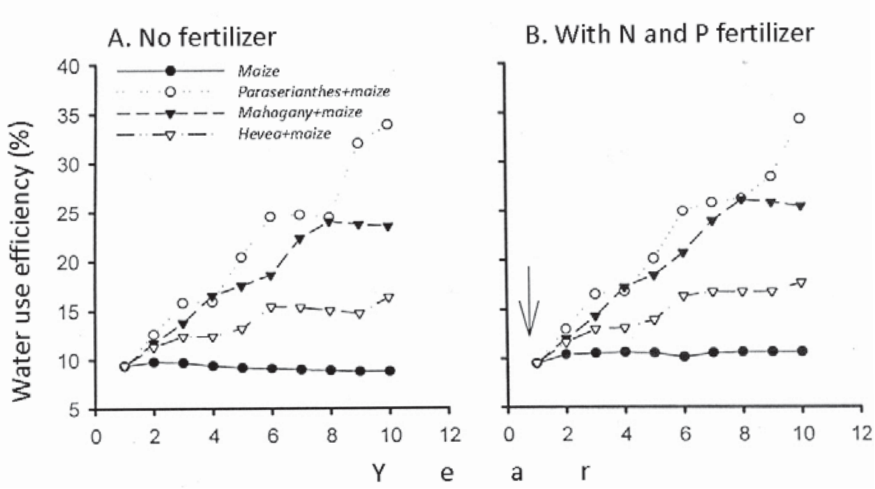


Figure 4.11. Water use efficiency at different agroforestry systems: maize monoculture, *Paraserianthes* + maize, *Mahogany* + maize and *Hevea* + maize. (A) no fertilizer and (B) with N and P fertilizer.

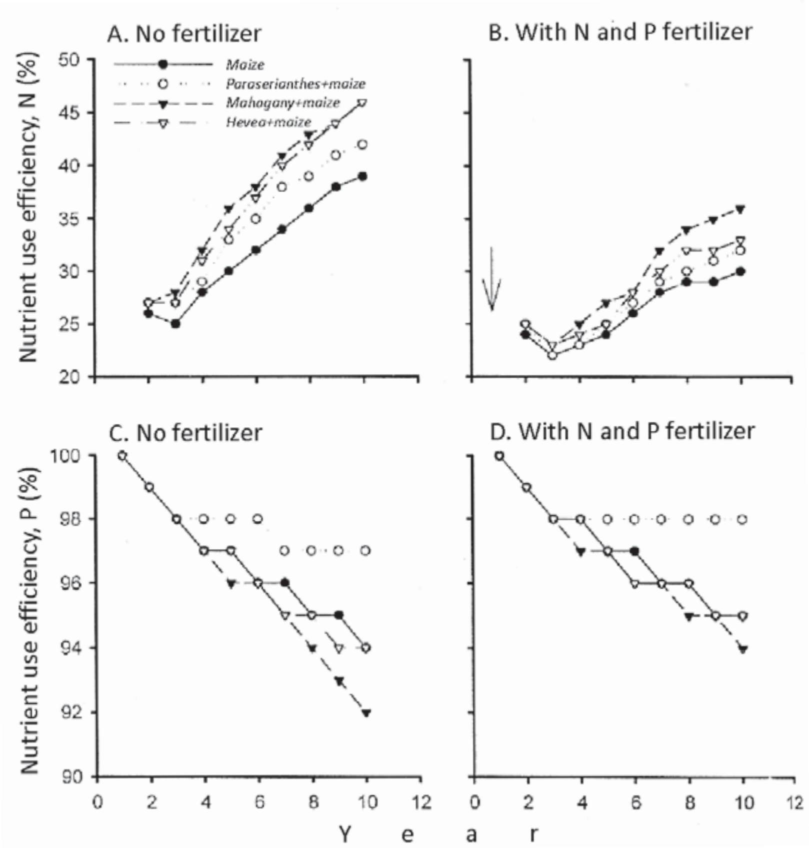


Figure 4.12. Nutrient (N and P) use efficiency in the different agroforestry systems : maize monoculture, *Paraserianthes* + maize, *Mahogany* + maize and *Hevea* + maize. (A and C) no fertilizer and (B and D) with N and P fertilizer.

4.11. Management options for agroforestry parkland systems in Sapone (Burkina Faso): separating the tree-soil-crop interactions using WaNuLCAS

Trees in the parkland systems of West Africa provide food and income, but also interact with the grain crops. Competition and complementarity in resource use between the components of these systems need to be better understood. The effects of crown pruning of agroforestry parkland systems in terms of resource capture and utilization either were investigated in an agroforestry parkland system in Burkina Faso or was analysed using the Water Nutrient and Light Capture in Agroforestry Systems (WaNuLCAS) (Bayala , *et al*, 2004).

The tree was focus on two species *Vitellaria paradoxa C.F. Gaertn (karité)* and *Parkia biglobosa (Jacq.) Benth. (néré)* with associated crops of *Pennisetum glaucum (L.) (millet)* and *Sorghum bicolor (L.) Moench (sorghum)*. Three treatments of crown pruning (totally-pruning, half-pruning and no-pruning) were applied to karité and néré. The area under each tree was divided into four concentric tree influence zones before pruning the trees (Zones A: up to 2 m from the tree trunk, B: up to half of the radius of the tree crown, C: up to the edge of the tree crown and D: up to 2 m away from the edge of the tree crown).

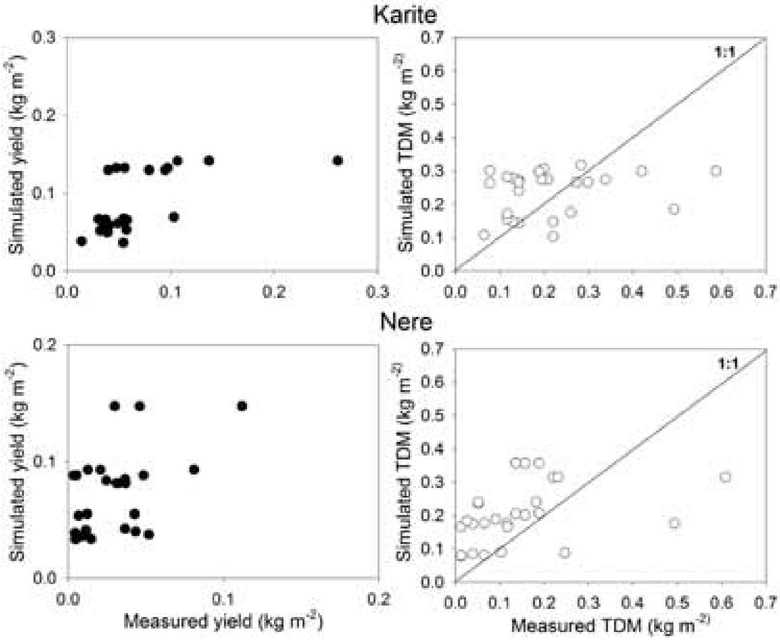


Figure 4.13. Scatter plots of measured and simulated crop yield and total dry matter (TDM) under karité (Vitellaria paradoxa) and néré (Parkia biglobosa) trees in a parkland agroforestry system in Saponé, Burkina Faso.

Figure 4.13 shows crop performance for the various zones and pruning regimes tended to be overestimated, indicating that not all limitations occurring tin the field were adequately represented and/or that resource capture for the resources included in the model (light, water, N and P) was overestimated. Simulation with WaNulCAS indicated that the plant components differed in the key limiting factors. For the Karite, with a relatively shallow root system and ability to fix atmospheric nitrogen, water limitation dominated for (29%, 27% and 33% of the simulation period for unpruned, half-pruned and totally pruned trees, respectively). Water limitation was also found to restrict crop growth under this species (26% of the time in unpruned and half-pruned trees, and 30% of the growing season for totally pruned) trees. P limitation restricted crop growth only 8% of the season in unpruned and half-pruned trees and 4% in totally pruned trees. Water limitation under karite is probably due to its shallow root system indicating its high dependency on rainfall water and probable less access to the ground water table. For the Nere tree the main limitations were water (11 to 32% of the simulation time) and P (15 to 42 of the simulated time). Crop growth under Nere was mainly limited by P (32 to 50% of the simulated growing season) corroborate to the findings of Tomlinson *et al*. (1995) and Bayala *et al*. (2002).

4.12. Long time effect of Legume Cover Crop (LCC), sugarcane harvest residue (trash) and *Bagas* (sugarcane processing waste) on soil carbon and sugarcane yield

Ultisols is a typical soil type in North Lampung, Indonesia. It is low in soil organic matter content as well as N, P and exchangeable cations. It also has high concentration of Al and Mn. Thus, the main problem in soils of North Lampung is low fertility.

Soil organic matter is the key factor to soil fertility. One way to prevent more soil degradation is to maintain soil organic matter. Maintaining soil cover throughout the year, either by cover crop or by mulch, can do this. A continuous biomass is required to stabilize the organic matter content of the soil. According to Young (1989) about 8.5 Mg ha^{-1} annual input of aboveground biomass is required in order to maintain soil carbon content of 2 %.

One of the main crops in North Lampung is sugarcane. Sugarcane yields tend to drop rapidly if there is no fertilizer input. A potential source organic input to the systems is sugarcane harvest residue (*trash*) and *Bagas* (sugarcane processing waste). *Thrash* is normally burnt after harvest and *Bagas* (sugarcane processing waste) is normally piled up around the sugarcane factory creating high risk of fire.

Brawijaya University-Indonesia had conducted an experiment to test the effect LCC, sugarcane harvest residue (trash) and Bagas (sugarcane processing waste) on sugar cane growth and production. The following applications of organic materials were tested on a soil that had been cropped for more than 10 years after forest conversion: (1) without organic materials as a control, (2) bagas 8 Mg ha^{-1}, (3) bagas 16 Mg ha^{-1}, (4) sugarcane trash (harvest residue) 8 Mg ha^{-1}. The whole plot was planted a mixed of legume cover crops (LCC) *Mucuna pruriens var. utilis* and *Centrosema pubescens* (1:1) and was given rock phosphate 1 Mg ha^{-1} at the first year and followed by sugarcane for another 2 years.

Based on this experiment, we simulate the systems using WaNuLCAS model to see the long-term effect of the organic inputs on soil fertility (Hairiah, *et al*., 2003). Three different scenarios were used: (1) external organic input given only at first year and N and P fertilizer every years with similar dosage, (2) external organic input gave every three years and N and P fertilizer every years with same dosage, (3) external organic input gave every three years and N and P fertilizer every years with different dosage (ratio dosage/years = 1.2:0.9:0.9 from default value and start from third years).

The simulation predicted that additional organic input do not significantly affect the long-term amount of organic carbon of the systems (Figure 4.14). The organic matter content at 0 – 5 cm depth decrease by 0.04 – 0.07% per year, which is faster compare to 0.02 – 0.03 % per year at depth 5-20 cm.

The results also predicted that application of sugarcane residues to the soil lead to a slower declining rate of sugar cane yield if accompanied by application of N fertilizer (Figure 4.15). Without N fertilizer application, returning sugarcane residues will cause N immobilization in the soil causing a decrease in sugarcane yield.

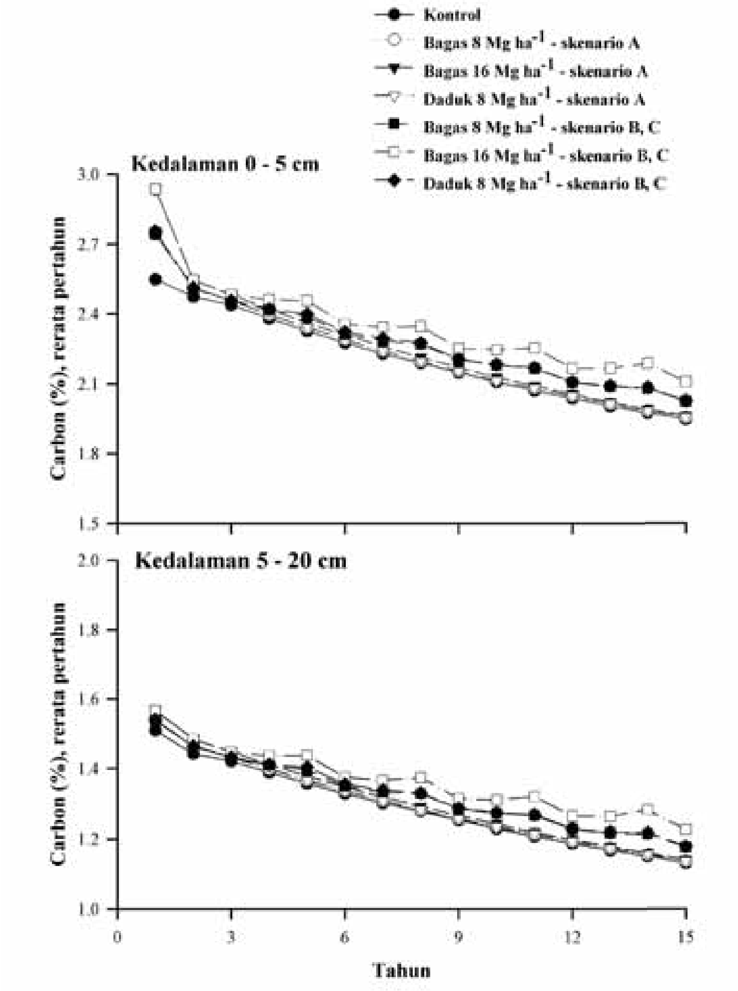


Figure 4.14. Soil organic matter content (average per year) at depth 0 – 5 and 5 – 20 cm of soil.

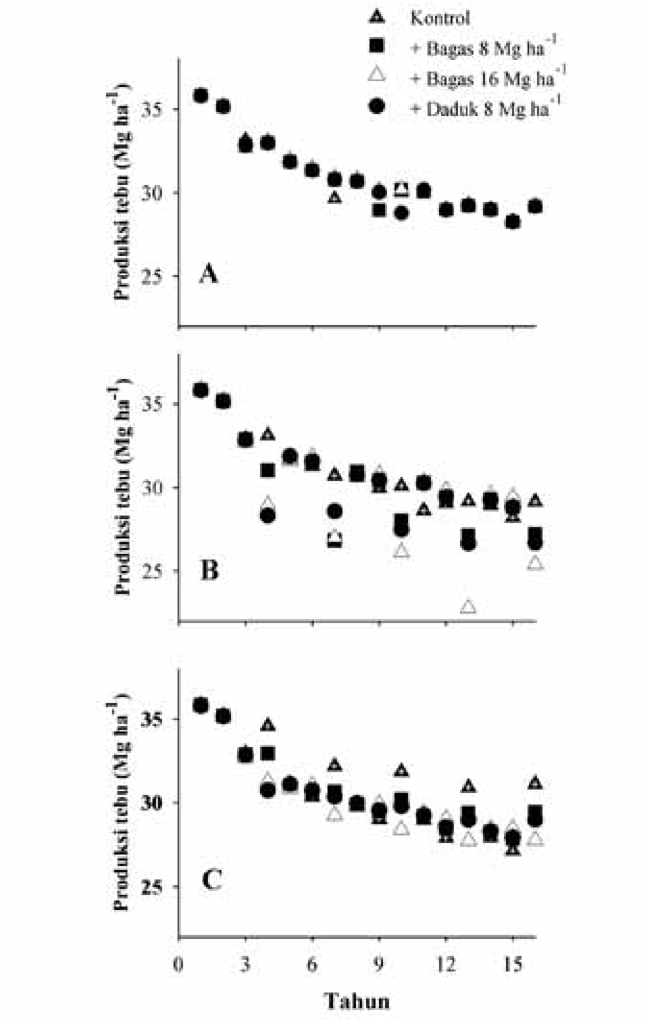


Figure 4.15. Sugarcane yield (in dry weight stem, Mg ha-1) for 16 years in different treatment and scenario.

4.13. The effect of agroforestry systems based on differing leaf phenologies on water balance and tree and crop growth

In Thika and NaroMoru, West of Mt. Kenya introduction of tree species into the cropping systems might aggravate the crop since water limitation is an important factor for the crop performance and yield. The differences of crop performance and yield may have relation to the tree water uptake that is corroborate to the tree leaf phonologies. The WaNuLCAS model was used to simulate water balance of the agroforestry systems based on differing leaf phenologies (Muthuri, 2003). The tree was focus on three species *G. robusta, A. acuminata* and *P. fortunei* associated with maize. *G. robusta* is evergreen, *A. acuminata* is semi-deciduous and *P. fortunei* is deciduous in term of tree water uptake.

Figure 4.16 and 4.17 shows the components of the water balance by the trees and crops using different leaf phenology for the Thika and Naro Moru site. The simulations of the water balance between Thika and Naro Moru site shows was not too different. Changing leafing phenology from evergreen, through semi-deciduous to deciduous generally decreased water uptake by the trees and interception of rainfall by all three trees species. Simulated total water uptake was never greater in all agroforestry systems than in sole maize, although the estimated water uptake by the crop component in the agroforestry systems was close to that for sole maize, especially when the deciduous leafing phenology scenario was adopted.

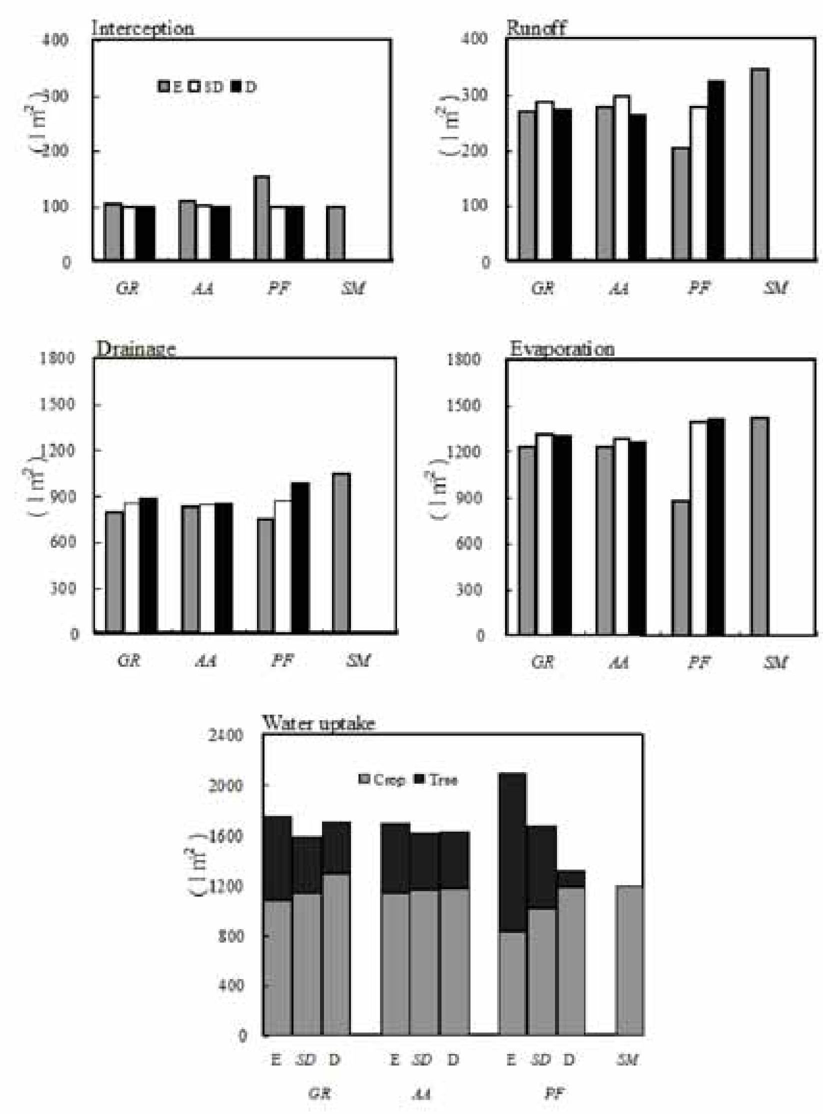


Figure 4.16. Simulated values for water balance components in (SM) sole maize and agroforestry systems containing (GR) *G. robusta*, (AA) *A. acuminata* and (PF) *P. fortunei* in five year simulation involving (E) evergreen, (SD) semi deciduous and (D) deciduous leaf phenology scenarios at Thika.

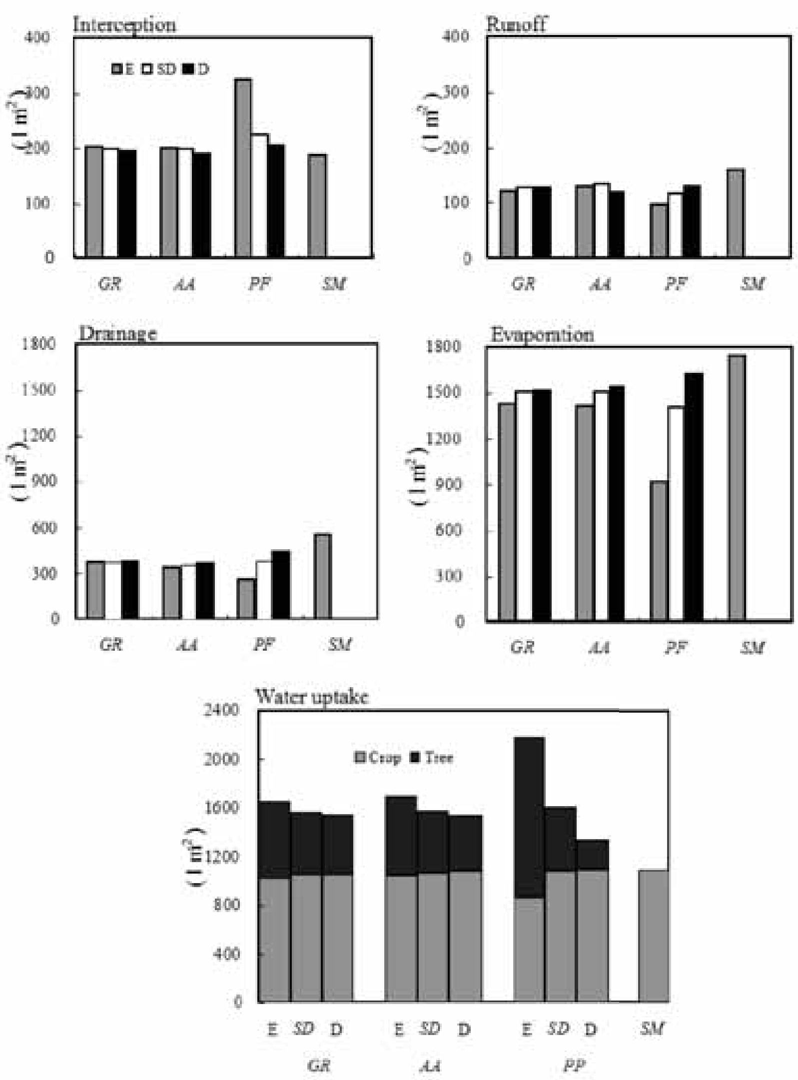


Figure 4.17. Simulated values for water balance components in (SM) sole maize and agroforestry systems containing (GR) *G. robusta*, (AA) *A. acuminata* and (PF) *P. fortunei* in five year simulation involving (E) evergreen, (SD) semi deciduous and (D) deciduous leaf phenology scenarios at Naro Moru.

4.14. Safety net efficiency – effect of root length density and distribution

The presence of hedgerow tree in the crop field may lessen nutrient leaching. For nutrients of higher mobility leaching could be reduced if tree have a relatively dense root system beneath the crop root zone (a safety net). Cadisch *et al.*, 1997 have explore how such safety net function may depend on tree root length density in the layer underneath the crop root zone. WaNuLCAS was used to test the positive (safety net functions) and negative (competition for water and N) impacts of simultaneous tree roots on maize yield by separating relative tree root distribution from absolute root length density for topsoil and subsoil (van Noordwijk and Cadish, 2002).

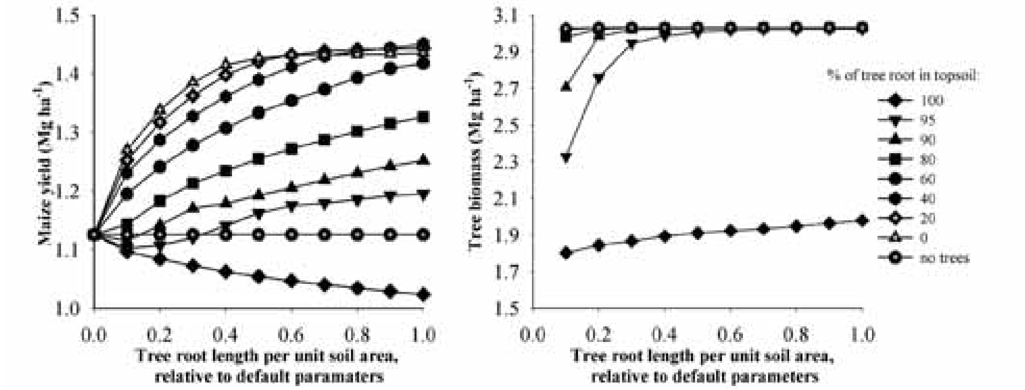


Figure 4.18. Predicted maize yield (A) and tree biomass (B) for the default rainfall situation (2318 mm year $^{-1}$), when relative distribution of tree roots with depth as well as total amount of tree roots are varied independently. Whereas the 'default' tree roots system had 21.5% of its roots in the top layer, a series of data was made that had 0 – 100% of its roots in the top layer and the remainder allocated to the deeper layers in proportion to the root length densities of the default case (the relative distribution over the four zones with increasing distance to the tree was not modified). For each of these root distributions, the total amount of roots was varied from 0.1 – 1 times the default, while maintaining the relative value.

Figure 4.18 shows that negative effect of the tree can be expected from trees that have all their roots in the topsoil, and from trees with only 0 – 10% of their roots in the subsoil, at low overall tree root length. These same relative tree root distributions at higher total root length (i.e. higher absolute root lengths in both top and subsoil) can have a moderate positive effect on maize yield, while tree root systems with 20% or more of their roots in the subsoil were consistently positive for crop, the higher the total root length, the more positive the impact on maize.

A remarkable feature of these results is that at default value for total root length, the tree root systems with 60% of their roots below the top soil led to (slightly) higher maize yields, than those with more (up to 100%) in the subsoil, while at total root systems size the 100% in subsoil (0% in top soil) was better for the maize. Although this effect is much too subtle to be recognized in any field data, it seems counter-intuitive.

4.15. Tree root systems dynamic – root functional and local response

Simulation models can represent belowground resource capture process at different levels of sophistication (van Noordwijk and De Willigen, 1987):

- Level 0.
  models 'without roots' using empirical resource capture efficiency coefficients for the relation between water and nutrient supply in the soil and the dynamics of plant growth,

- Level 2.
  models that differentiate between soil layers and use empirical data on relative root distribution to predict resource capture potential in each zone; root distribution can be schematised via an exponential decrease with depth (Jackson *et al*. 1996) or its 2-dimensional elliptical variant (Van Noordwijk *et al*., 1995), or they can be provided as 'independent' parameters for each layer or zone; change of root length densities with time can be imposed on the basis of crop age,
- Level 3.
  models that consider plants as organisms with the capacity to adjust the total amount of roots to the internal balance between above and belowground resource capture, and the location of new root growth to the parts of the root system with the best opportunities for uptake of the resource that is most limiting overall plant growth.

WaNuLCAS model can predict competition for water and nutrients between trees and crops at 'level 0' and 'level 1'. It can also be used at 'level 2' using spatial root distribution that restrictedly follows the exponential-decrease-with-depth or elliptical distributions. Stress of nutrient (N, P) or water is an important factor for the crop growth. When nutrient (N, P) or water stress occurs, the relative allocation of growth reserves to root can increase quickly.

The WaNuLCAS model was used to explore the change of root patterns due to local response (van Noordwijk, *et al*., 2003). A series of simulations was made for a moderately deep soil (1 m) with an annual rainfall of 1000 mm. Rainfall patterns ranged from '1 = every day 3 mm of rain' and '2 = every second day 6 mm', to '6 = every 32 days 96 mm'. As the potential evapotranspiration was assumed to be 4 mm day^{-1}, this environment would not provide enough water to avoid water stress, even if all rainfall were to be fully used. Figure 4.19 shows the rainfall patterns lead to situations of permanent moderate stress (rainfall pattern 1), alternations of sufficient water and severe water shortage (rainfall patterns 5 and 6) or intermediate patterns. In the overall water balance, with a decrease in the number of rainy days (through patterns 1 to 6), a decrease in the values for the interception and soil evaporation terms can be noted, while the contribution to groundwater (deep infiltration) and runoff increases but remains small in absolute value. Cumulative tree water use tends to increase through rainfall patterns 1 to 6. If a grass sward is added to the simulations, canopy interception increases and thus the amount of soil water available to either tree or grass is reduced. The grass water use is predicted to benefit more from rainfall patterns 5 and 6 than the tree causing a bell-shaped response curve for the tree.

A sensitivity analysis was carried out on the two key parameters for the functional shoot/root balance and root distribution: 'Root_Allocation_Responsiveness' and 'local response'. Higher values of 'Root_Allocation_Responsiveness' lead to a more rapid shift of current growth resources to roots, at the expense of shoot growth, when the total uptake of water and/or nutrients falls short of current 'demand'. With increasing 'local response', root distribution shifts towards the soil layer and spatial zone in which roots are most successful (per unit root length) in taking up the most limiting resource.

'Local response' is simulated in WaNuLCAS by a gradual change in the parameters of the elliptical root distribution, and constrained by the total new length of roots that can be produced with the carbohydrates allocated. The intensity of change depends on the T_DistResp parameter and on the degree to which effective uptake per unit root length of the currently limiting resource differs between soil layers and zones. If roots in deeper layers are more effective (e.g. in case of water stress), the root distribution can shift to a more gradual decrease of root length density with depth (or even an inverse pattern), if roots in topsoil are more effective (e.g. when P uptake is overall limiting plant growth and the topsoil has sufficient water content to keep the P mobile) roots will expand (mainly) in topsoil.

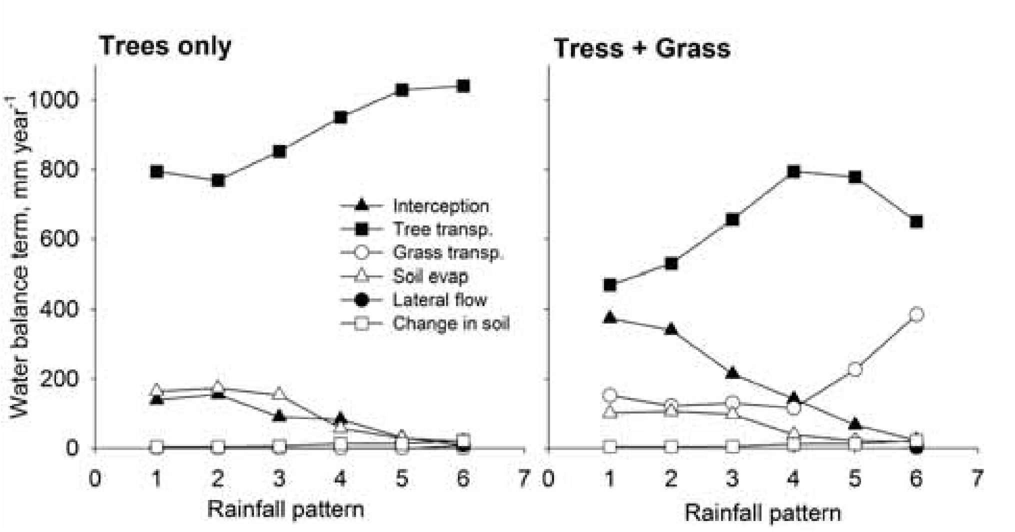


Figure 4.19. Water balance for a range of WaNuLCAS simulations, in the absence of functional or local response of the tree, with and without a grass sward.

The general patterns of root and shoot response in the simulations can be understood from the re-wetting patterns of the soil (Figure 4.20). In the absence of a competitor, a stronger root allocation leads to a larger root system, but only in rare situations to a larger shoot biomass or total water use. For rainfall patterns 1-4 the ‘local response’ rules lead to a shallower tree root system, as the rainfall events are insufficient to rewet the whole soil profile and superficial roots are thus more effective in water uptake than deep ones. For rainfall pattern 5 and 6, however, the local response rule leads to a deeper root system. In the presence of a competing grass sward, total water use by the tree is expected to decrease substantially and the tree biomass will consequently be lower. A marked difference with the previous simulations, however, is that now a larger root allocation can actually increase tree water use and shoot biomass. The competitor is predicted to enhance the increase in the fraction of tree roots in the topsoil for rainfall pattern 1-4. For rainfall pattern 5 the presence of a grass sward is predicted to drive the tree root to a more superficial pattern, rather than the deeper pattern of the monoculture.

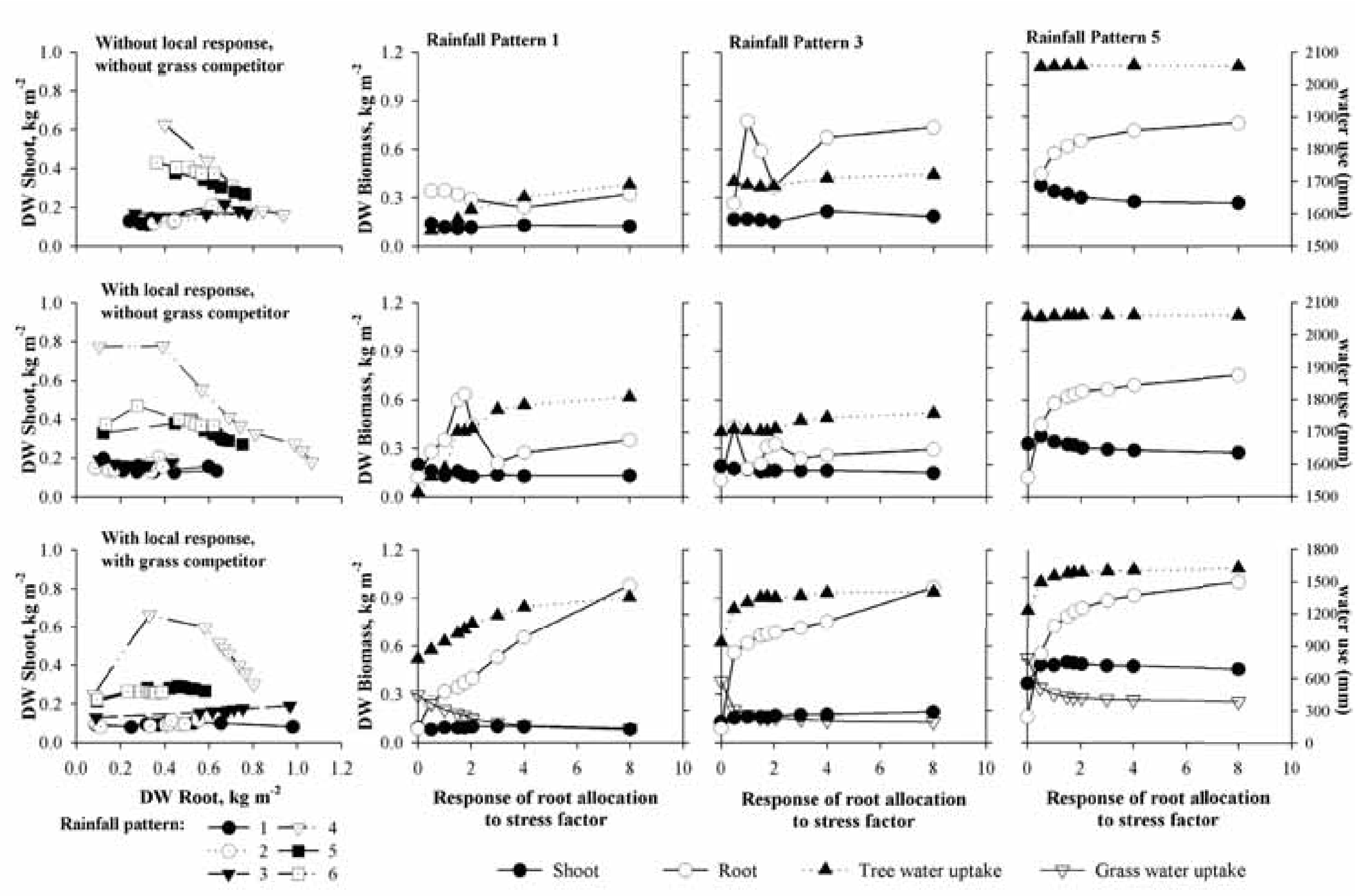


Figure 4.20. Simulation results for shoot and root dry-weight (DW) biomass and tree (and grass) water use, for three rainfall patterns and a range of parameter values for the 'root_Allocation_Responsiveness' parameter (see explanations in text, this Box). Simulations include situations with and without 'local response' (see text, this Box), and with and without competition from a grass sward

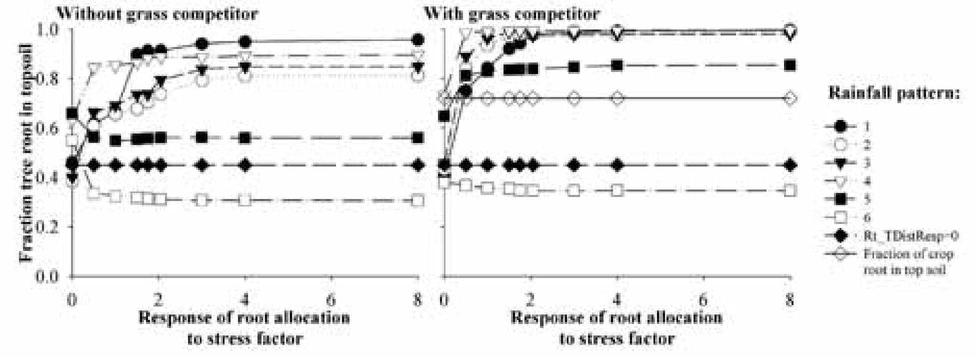


Figure 4.21. Relative tree root biomass in the upper 25 cm of the soil profile for a range of values of the factor that governs the response to stress of the biomass allocation to roots, with (right) and without (left) a competing grass; the grass is assumed not to show a functional or local response, so it has a constant fraction of its roots in the topsoil; the line Rt_TdistResp = 0 indicates a situation without 'local response', so the 'response to stress' can modify total root biomass, but not root distribution for this setting.

4.16. Improved options for tree spacing and tree-crop intercrop patterns

Transformations from degraded soils and landscapes to agroforestry mosaics can benefit from the potential complementarity between the early stages of tree-based production systems and crop growth. Decisions by farmers managing such transition involve strategic (multi-year) decisions on the choice of tree species, the number of trees per ha and the spacing, while tactical (shorter term) decisions relate to the choice of intercrops, tree canopy pruning and/or tree root pruning. Based on the current experience in Lampung (Indonesia) through SAFODS (Smallholder agroforestry options for degraded soils: Tree establishment in cropped fields) project, we use WaNuLCAS model to explore these choices.

Increasing the space between tree rows makes longer intercropping possible – but also reduces the expected yield from the trees. An efficient way of considering the trade-off is to plot crop versus tree yield (Figure 4.22).

Most of the tree- crop combinations are substantially above the straight trade-off curve, suggesting that there is indeed a benefit to be obtained by the combination when compared to separate monocultures. However, the points for *A. mangium* suggest virtually no intercropping advantage. For the slower growing trees (mahogany and rubber), maximum tree yield can be obtained at about 20% of the potential long-year crop yield. After accounting for this intercept, a slight positive curvature remains when tree spacing is widened. *P. falcataria* has a low intercept (low crop yield opportunity when maximum wood volume is the target), but clear intercropping advantage at lower tree population density. This may therefore well be the most promising 'agroforestry' tree at intermediate densities.

As a first approximation of the dynamic effects of tree root pruning, we can compare simulations with and without the presence of tree roots in the various soil layers of the 'crop zone'. We assume that tree root pruning will have little effect on tree roots in the deeper layers, although the specific impacts on root distribution depend on tree species, time of pruning and soil conditions. According to the WaNuLCAS model set up for conditions in Lampung, we expect a direct negative effect of such tree root pruning on tree growth, and only a small positive effect on crop growth (Figure 4.23).

Tree root pruning will, according to the model, only have a substantial positive effect on opportunities for crop production in mahogany (*S. macrophylla*) and sengon (*P. falcataria*). The negative effects on tree growth will make this intervention not very attractiv4e, even before we account for the additional labour involved. Tree root pruning is a poor substitute for starting at an appropriate tree spacing.

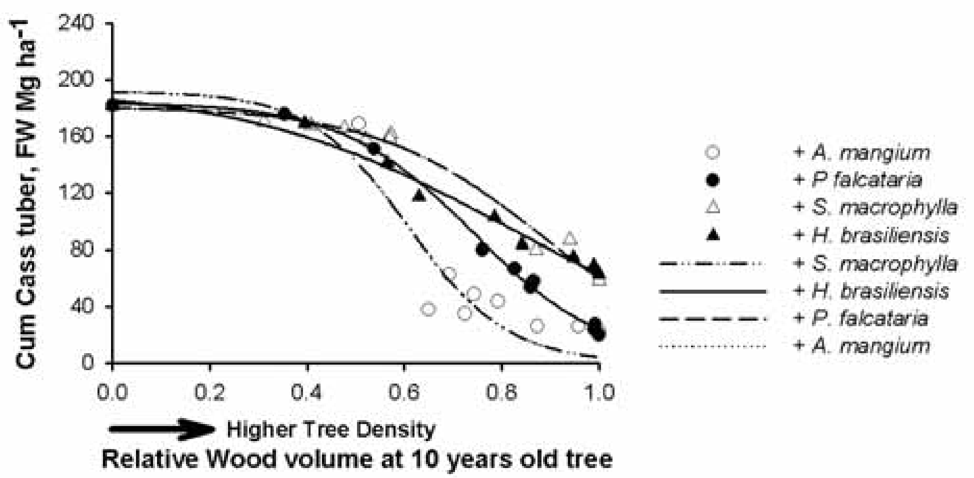


Figure 4.22. Predicted tradeoff between cumulative cassava yield and wood volume at various tree species and densities in Lampung.

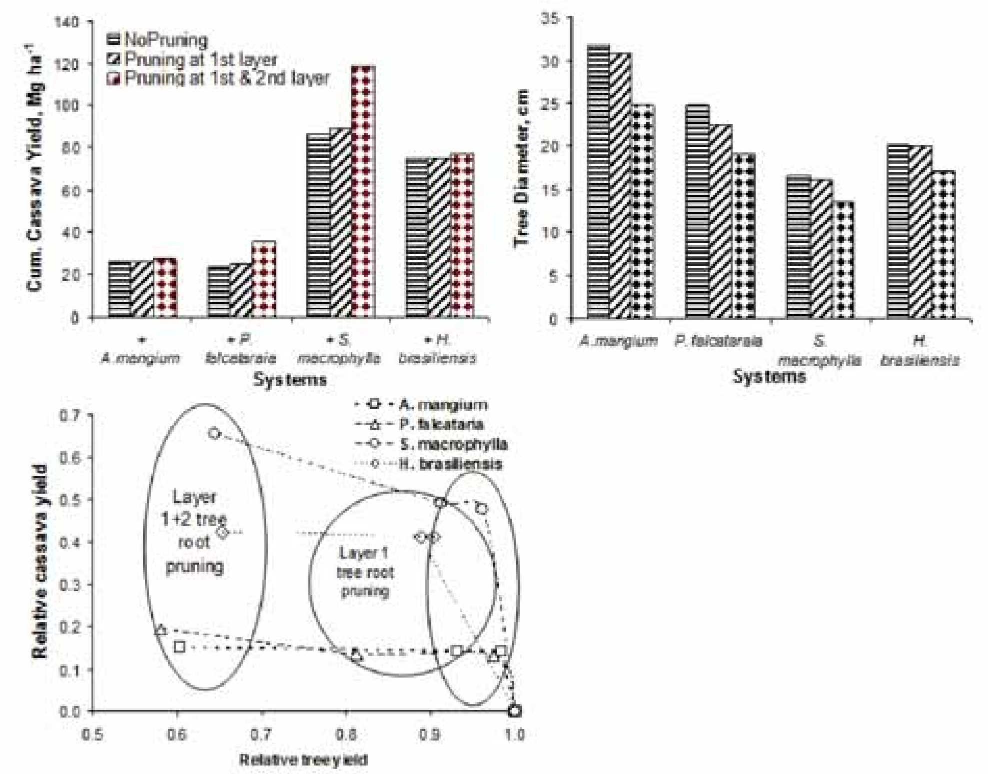


Figure 4.23. Upper limit of effects of tree root pruning on predicted performance of a cassava crop (A), tree growth (B) and on the tradeoff (C) between expected tree and crop yield under Lampung conditions; the simulation compared default conditions with situations without tree roots in the first or the first two layers fro all cropped zones

4.17. Recommendations for shade-based Imperata control during tree establishment

Technically, Imperata as a weed can be controlled and Imperata grasslands can be converted to more productive systems. The first steps in technically controlling Imperata in the agroforestation of grasslands can be achieved by either mechanical or chemical control. Farmers employ a range of techniques from herbicide or soil tillage to 'pressing', depending on their resources and the current cost of the technique. Food crops can be used in the first few years of most tree crops or agroforestry systems to maintain income and pay for the suppression of Imperata regrowth. However, the gap between the last food crop interplanting and canopy closure leads to a major risk of Imperata regrowth and fire occurrence. The current analysis of shade-based Imperata control by agroforestation is largely focussed on the duration of this 'Imperata regrowth window', and the way its duration depend on the planting pattern and species choice of the trees.

Through SAFODS (Smallholder agroforestry options for degraded soils: Tree establishment in cropped fields) project, we compared WaNuLCAS model scenarios between tree species to estimate the Imperata regrowth window as the period between 50 and 15% of ground-level light availability.

Results of the WaNulCAS model simulations first of all confirmed a well-known fact: young trees of most species are not able to compete with Imperata and partial weeding around the tree stem base is absolutely necessary to get most trees started, with the possible exception of *Paraserianthes falcataria*. Although *Acacia mangium* is a fast growing tree, a more intensive weeding regime will double tree growth. The improvement of initial tree growth speeds up tree canopy closure and reduces subsequent Imperata regrowth window is 2 to > 5 years according to the model, with periods longer than 5 years associated with slow initial growth rates (Figure 4.24).

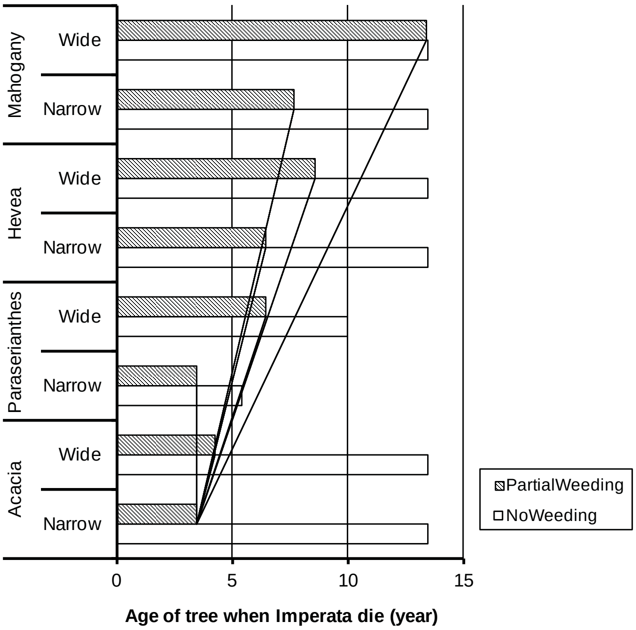


Figure 4.24. The age of the tree when Imperata die of four tree species under different weeding regime (partial and no weeding) and different tree spacing, narrow (timber trees : 4*2, 3*3, 4*4 m; rubber : 6*3, 5*3, 4*4 m) and wide spacing (timber trees : 8*4, 8*8 m; rubber : 6*6, 12*6m).

References

Akyeampong E, Duguma B, Heineman AM, Kamara CS, Kiepe P, Kwesiga F, Ong CK, Otieno HJ and Rao MR (1995) A sysntesis of ICRAF's research on alley cropping. *In*: Alley Farming Research and Development. AFNETA, Ibadan, Nigeria. Pp 40 – 51.

Akyeampong E, Duguma B, Heineman AM, Kamara CS, Kiepe P, Kwesiga F, Ong CK, Otieno HJ and Rao MR (1995) A synthesis of ICRAF's research on alley cropping. *In*: Alley Farming Research and Development. AFNETA, Ibadan, Nigeria. pp 40-51.

Arah J and Hodnett M (1997) Approximating soil hydrology in agroforestry models. Agroforestry Forum 8(2): 17-20.

Bayala J, van Noordwijk M, Lusiana B, Ouédraogo S J, Teklehaimanot Z (2004) Separating the tree-soil-crop interactions in agroforestry parkland systems in Sapone (Burkina Faso) using WaNuLCAS. ICRAFSEA – INERA. Poster presented at 1st World Congress of Agroforestry, 27 June – 2 July 2004, Orlando – Florida, USA.

Boughton, WC (1999) A daily rainfall generating model for water yield and flood studies. Cooperative research centre for catchment hydrology. 21 pp.

Breman H and Kessler JJ (1997) The potential benefits of agroforestry in the Sahel and other semi arid regions. European Journal of Agronomy 7: 25 33.

Burgess SSO, Adams MA, Turner NC and Ong CK (1998) Redistribution of soil water by tree root systems. Oecologia 3(115): 306-311.

Cadisch G, Rowe E and van Noordwijk M (1997) Nutrient harvesting - the tree-root safety net. Agroforestry Forum 8(2): 31-33.

Caldwell RM, Pachepsky YA and Timlin DJ (1996) Current research status on growth modeling in intercropping. *In*: O.Ito *et al*. (*Eds*) Dynamics of Roots and Nitrogen in Cropping Systems of the Semi-Arid Tropics. Japan International Research Center for Agricultural Sciences. pp 617-635.

Cannell MGR, Mobbs DC and Lawson GJ (1998) Complementarity of light and water use in tropical agroforests. II. Modelled theoretical tree production and potential crop yield in arid to humid climates. Forest Ecology and Management 102: 275 282.

Cannell MGR, van Noordwijk M and Ong CK (1996) The central agroforestry hypothesis: the trees must acquire resources that the crop would not otherwise acquire. Agroforestry Systems 33: 1-5.

Dawson TE (1993) Hydraulic lift and water use by plants: implications for water balance, performance and plant plant interactions. Oecologia 95: 565 574.

De Willigen P and Van Noordwijk M (1987) Roots for plant production and nutrient use efficiency, Doctoral thesis Agricultural University Wageningen 282 pp.

De Willigen P and Van Noordwijk M (1989). Model calculations on the relative importance of internal longitudinal diffusion for aeration of roots of non-wetland plants. Plant Soil 113: 111-119

De Willigen P and Van Noordwijk M (1989) Rooting depth, synchronization, synlocalization and N use efficiency under humid tropical conditions. *In*: Van de Heide, J. (*eds*) Nutrient Management for Food Crop Production in Tropical Farming Systems. Institute for Soil Fertility, Haren, pp. 145 156.

De Willigen P and Van Noordwijk M (1991) Modeling nutrient uptake: from single roots to complete root systems. in: F.W.T. Penning de Vries, HH van Laar and MJ Kropff (*eds*) Simulation and Systems Analysis for Rice Production (SARP). Simulation Monographs, PUDOC, Wageningen. p. 277-295.

De Willigen P and Van Noordwijk M (1994) Diffusion and mass flow to a root with constant nutrient demand or behaving as a zero-sink. Soil Sci. 157: 162-175.

De Willigen P, Nielsen NE, Claassen N and Castrignanò AM (2000) Modelling water and nutrient uptake. In: A.L. Smit, A.G. Bengough, C. Engels, M. Van Noordwijk, S. Pellerin and Van der Geijn (*eds*) 2000. Root Methods, a Handbook. Springer Verlag, Berlin. pp 509-544

Duan J, Sikka AK, Grant GE (1995) A Comparison of stochastic models for generating daily precipitation at the H.J. Andrews Experimental Forest. Northwest Science 69 (4): 318-329.

Geng S, De Vries P, Supit FWTI (1986) A simple method for generating daily rainfall data. Agricultural and Forest Meteorology 36: 363-376.

Gijsman AJ, Oberson A, Tiessen H and Friesen DK (1996) Limited applicability of the CENTURY model to highly weathered tropical soils. Agron. J. 88: 894-903.

Gotelli ND and Graves GR (1996) Null Models in Ecology. Smithsonian Institution Press, Washington, 357 pp.

Hairiah K, Purnomosidhi P, Khasanah N, Nasution N, Lusiana N, and van Noordwijk M (2003) Pemanfaatan Bagas dan Daduk Tebu untuk Perbaikan Status Bahan Organik Tanah dan Produksi Tebu di Lampung Utara: Pengukuran dan Estimasi Simulasi WaNuLCAS (Use of bagas and sugarcane trash to improve soil organic matter status and sugarcane yield in North Lampung: field measurement and simulation by WaNuLCAS model) . Agrivita Vol. 25 No. 1

Hannon B and Ruth M (1994) Dynamic Modeling. Springer-Verlag, New York. 248 pp.

Howard SB, Ong CK, Black CR and Khan AAH (1997) Using sap flow gauges to quantify water uptake by tree roots from beneath the crop rooting zone in agroforestry systems. Agrofor. Syst. 35: 15 29.

Kropff MJ and Van Laar HH (1993) Modeling crop - weed interactions. CAB International, Wallingford (UK).

Lott JE, Khan AAH, Ong CK and Black CK (1996) Sap flow measurements of lateral roots in agroforestry systems. Tree Physiol 16: 995 1001.

Mobbs DC, Cannell MGR, Crout NMJ, Lawson GJ, Friend AD and Arah J (1998) Complementarity of light and water use in tropical agroforests. I. Theoretical model outline, performance and sensitivity. Forest Ecology and Management 102: 259 274.

Muetzelfeldt R and Taylor J (1997) The suitability of AME (Agroforestry Modeling Environment) for agroforestry modeling. Agroforestry Forum, 8(2) 7-9.

Muthuri, C. W. (2004). Modelling leaf phenology effects on water use and growth; In Impact of agroforestry on crop performance and water resources in semi-arid central Kenya. PhD thesis, Jomo Kenyatta University of Agriculture and Technology, Kenya, pp 222-251.

Myers B, Van Noordwijk, M and Vityakon P (1997). Synchrony of nutrient release and plant demand: plant litter, soil environment and farmer management options. *in*: G. Cadisch and K.E. Giller (*eds*) Driven by Nature: Plant Litter Quality and Decomposition. CAB International, Wallingford (UK) pp. 215 - 229.

Myers RJK, Palm CA, Cuevas E, Gunatilleke IUN and Brossard M (1994) The synchronisation of nutrient mineralisation and plant nutrient demand. *in*: P.L. Woomer and M.J. DSwift (*Eds*.) The Biological Management of Tropical Soil Fertility. Johm Wiley, Chichester (UK) pp 81-116.

Ong CK 1995. The 'dark side' of intercropping: manipulation of soil resources. In: Sinoquet H and Cruz P (*eds*.) Ecophysiology of Tropical Intercropping, 482 pp. Institute National de la Recherche Agronomique, Paris (France).

Ong CK and PA Huxley (*Eds*.). (1996) Tree-Crop Interactions - a Physiological Approach. CAB International, Wallingford (UK).

Palm CA, Alegre JC, Arevalo L, Mutuo PK, Mosier AR and Coe R (2002) Nitrous oxide and methane fluxes in six different land use systems in the Peruvian Amazon. Global Biogeochemical Cycles 16(4), 1073.

Parton WJ, Ojima DS, Cole CV and Schimel DS (1994) A general model for soil organic matter dynamics: sensitivity to litter chemistry, texture and management. *In*: Quantitative Modeling of Soil Forming Processes. Special Publication 39, Soil Science Society of America, Madison WI, USA, pp 147-167.

Pickering NB, Stedinger JR, Haith DA (1988). Weather input for nonpoint source pollution models. J. Irrig. Drain. Eng. 114 (4): 674-690.

Radersma S and Ong CK (2004) Spatial distribution of root length density and soil water of linear agroforestry systems in sub-humid Kenya: implications for agroforestry models. Forest Ecology and Management, 188(1-3), 77-89

Rao MR, Nair PK and Ong CK (1997) Biophysical interactions in tropical agroforestry systems. Agroforestry Systems 38: 3 - 49.

Richardson CW (1981) Stochastic generation of daily precipitation, temperature, and solar radiation. Water Resource Res. 17(1): 182-190.

Rodriguez RN (1977). A guide to the Burr type XII distribution. Biometrika 64: 129-134.

Rowe EC, Hairiah K, Giller KE, Van Noordwijk M and Cadisch G (1999) Testing the safety-net role of hedgerow tree roots by 15N placement at depths.. Agroforestry Systems 43: 81-93.

Rykiel EJ (1996) Testing ecological models: the meaning of validation. Ecological Modeling 90: 229-244.

Sanchez P (1995) Science in agroforestry. Agroforestry Systems 30: 5-55.

Scotter DR, Horne DJ, Green SR (2000). A procedure for generating daily rainfall and evaporation data: an evaluation and some applications. Journal of Hydrology (NZ) 39(1): 65-82.

Selker JS, Haith DA (1990). Development and testing of single-parameter precipitation distributions. Water Resources Res. 26: 2733-2740.

Shepherd KD and Soule MJ (1998) Soil fertility management in West Kenya: dynamic simulation of productivity, profitability and sustainability at different resource endowment levels. Agriculture, Ecosystems & Environment (in press).

Sinoquet H, Adam B, Rivet P and Godin C (1997) Interactions between light and plant architecture in an agroforestry walnut tree. Agroforestry Forum, 8(2) 37-39.

Smith DM, Jackson NA, Roberts JM and Ong CK (1998) Reverse flow in tree roots and downward siphoning of water by Grevillea robusta. Functional Ecology 2(13): 256-264.

Suprayogo D, Widianto and Lusiana B (2002) Diagnosis Kesehatan Bertani Berbasis Pohon: Apakah air dan hara tanah digunakan secara efisien. *In*: S.M. Sitompul and S.R. Utami (*eds*) Akar Pertanian Sehat: Konsep dan Pemikiran. Biological Management of Soil Fertility (BMSF), Brawijaya University, Malang (Indonesia). p 117-129

Suprayogo D, Widianto, Cadish G, and van Noordwijk M (2003) A Pedotransfer resource database (PTFRDB) for tropical soils : test with the water balance of WaNuLCAS *in*: D Post (*eds*) Proceedings of the 2003 MODSIM Conference – Volume 1. Townsville, Australia. p 584-589.

Suprayogo D (2000) Testing the Safety - Net Hypothesis in Hedgerow Intercropping: water balance and mineral - N leaching in the humid tropics. PhD thesis, Imperial College London, Wye Campus, UK, 316 pp.

Tomich TP, Van Noordwijk M, Budidarseno S, Gillison A, Kusumanto T, Murdiyarso D, Stolle F and Fagi AM (1998b) Alternatives to Slash-and-Burn in Indonesia, Summary report and synthesis of Phase II. ICRAF S.E. Asia, Bogor, Indonesia, 139 pp.

Tomich TP, Van Noordwijk M, Vosti S and Whitcover J (1998a) Agricultural Development with Rainforest Conservation: Methods for Seeking Best Bet alternatives to Slash-and-Burn, with Applications to Brazil and Indonesia. Agricultural Economics 19: 159-174.

Van Noordwijk M and De Willigen P (1984). Mathematical models on diffusion of oxygen to and within plant roots, with special emphasis on effects of soil-root contact: II. Applications. Plant Soil 77: 233-241

Van Noordwijk M and Brouwer G (1988). Quantification of air-filled root porosity: a comparison of two methods. Plant Soil 111: 255-258

Van Noordwijk M and Brouwer G (1993). Gas-filled root porosity in response to temporary low oxygen supply in different growth stages. Plant Soil 152: 175-185

Van Noordwijk M, Rahayu S, Williams SE, Hairiah K, Khasanah N, Schroth G (2003) Crop and tree root-system dynamics. *In:* M. van Noordwijk, G. Cadisch, C.K. Ong (*eds*) BelowGround Interaction in tropical Agroecosystems: Concepts and Models with multiple plant component, CABI, Wallingford, UK

Van Noordwijk M (1989) Rooting depth in cropping systems in the humid tropics in relation to nutrient use efficiency. *In*: J. van der Heide (ed.) Nutrient Management for Food Crop Production in Tropical Farming Systems. Institute for Soil Fertility, Haren. p 129-144.

Van Noordwijk M (1996a) A simple model to quantify mulch and shade effects. *In*: C.K. Ong and P.A. Huxley (*Eds*.). Tree-Crop Interactions - a Physiological Approach. CAB International, Wallingford (UK). pp 51-72.

Van Noordwijk M (1996b) Models as part of agroforestry research design. AGRIVITA 19: 192-197.

Van Noordwijk M and Brouwer G (1997) Roots as sinks and sources of carbon and nutrients in agricultural systems. *in*: L. Brussaard and R. Ferrera-Cerrato (*eds*.) Soil Ecology in Sustainable Agricultural Systems. CRC Lewis Publ., Boca Raton. pp 71-89.

Van Noordwijk M and Cadisch G (2002) Access and excess problems in plant nutrition. Plant and Soil 247:25-40

Van Noordwijk M and Lusiana B (1999) WaNuLCAS, a model of water, nutrient and light capture in agroforestry systems. Agroforestry Systems 43: 217-242.

Van Noordwijk M and Ong CK (1999) Can the ecosystem mimic hypotheses be applied to farms in African savannahs?.Agroforestry Systems 45: 131-158.

Van Noordwijk M and Purnomosidhi P (1995) Root architecture in relation to tree soil crop interactions and shoot pruning in agroforestry. Agroforestry Systems 30: 161-173.

Van Noordwijk M and Van de Geijn SC (1996) Root, shoot and soil parameters required for process-oriented models of crop growth limited by water or nutrients. Plant and Soil 183: 1-25.

Van Noordwijk M, Hairiah K, Lusiana B and Cadisch G (1998a) Tree - Soil - Crop Interactions in Sequential and Simultaneous Agroforestry Systems. *in*: L. Bergstrom and H. Kirschner (Ed.) Carbon and Nutrient Dynamics in Natural and Agricultural Tropical Ecosystems. CAB International, Wallingford (UK). pp 173-190.

Van Noordwijk M, Lawson G, Groot JJR, Hairiah K, (1996) Root distribution in relation to nutrients and competition. *In*: C.K. Ong and P.A. Huxley (*Eds*.). Tree-Crop Interactions - a Physiological Approach. CAB International, Wallingford (UK). pp 319-364.

Van Noordwijk M, Radersma S and Lusiana B (1999) Modelling root architecture and phosphorus uptake in agroforestry. Agroforestry Forum 9(4) 28-30.

Van Noordwijk M, Van Roode M, McCallie EL and Lusiana B (1998b) Erosion and sedimentation as multiscale, fractal processes: implications for models, experiments and the real world. *In*: F. Penning de Vries, F. Agus and J. Kerr (*Eds*.) Managing Soil Erosion. CAB International, Wallingford. 223-253.

Vandermeer JH (1989) The Ecology of Intercropping. Cambridge University Press, Cambridge.

Verchot LV, Davidson EA, Cattânio JH and Ackerman IL (2000) Land-use change and biogeochemical controls of methane fluxes in soils of eastern Amazonia. Ecosystems 3, 41-56.

Verchot LV, Davidson EA, Cattânio JH, Ackerman IL, Erickson HE and Keller M (1999) Land use change and biogeochemical controls of nitrogen oxide emissions from soils in eastern Amazonia. Global Biogeochemical Cycles 13, 31-46.

Verchot LV, Mosier A, Baggs EM and Palm CA (2004) Soil–Atmosphere Gas Exchange in Tropical Agriculture: Contributions to Climate Change. *In*: M. Van Noordwijk, G. Cadisch and C.K. Ong (*Eds*.) Belowground Interactions in Tropical Agroecosystems, CAB International, Wallingford (UK), in press

Wösten JHM, A Lilly, A Nemes and C Le Bas (1998) Using existing soil data to derive hydraulic parameters for simulation models in environmental studies and in land use planning. Report 156, SC-DLO, Wageningen (the Netherlands), 106 pp.

Wösten JMH, Finke PA and Jansen MJW (1995) Comparison of class and continuous pedotransfer functions to generate soil hydraulic characteristics. Geoderma 66: 27-37.

Young A (1997) Agroforestry for Soil Management. 2nd ed. CAB International, Wallingford (UK). 320 pp.

Young A, Menz K, Muraya P and Smith C (1990) SCUAF Soil changes under agroforestry. Computer program with user's handbook. Version 2. ICRAF, Nairobi (Kenya) 124 pp.

Young A, Menz K, Muraya P and Smith C (1998) SCUAF Version 4: A model to estimate soil changes under agriculture, agroforestry and forestry. ACIAR Technical Reports Series No. 41, ACIAR, Canberra (Australia). 49 pp.

Appendix

Appendix 1. Introduction to STELLA

STELLA is a flowchart-based modelling software. It enable users to construct model by drawing boxes, circles and arrows. **STELLA** is similar to ModelMaker.

During this session you will learn to build a model, step by step using **STELLA**. The purpose of this session is to familiarize yourself with **STELLA** and to learn how to use basic features of **STELLA** for simulation modelling.

Initiating **STELLA**

Start **STELLA** by clicking on its icon on the window screen. You will be automatically inside a new file.

STELLA is a multi-level hierarchical environment. It consists of 3 layers [3]:

- Interface Layer; which contain input output relationship
- Map and Model Construction Layer; where you construct the model can be simulated, it is often refered to as the 'engine room' for the models you create
- Equation Layer; to view list of all equation of model elements and relations

Move between layers

- Currently you are in the second layer. You can move between layers by clicking on arrow at the top left hand corner.
- You will find all the layers are still empty because you have not construct anything.

Let’s try building a simple model based on Trenbath (1984).

Trenbath formulated a simple model of restoration and depletion of ‘soil fertility’ during fallow and cropping periods, respectively.

‘Soil fertility’ is defined as a complex of effective nutrient supply and biological factors (diseases, weeds) affecting crop yield. Crop yield is assumed to be directly proportional to ‘soil fertility’.

Assume during a cropping period soil fertility declines with a fraction D per crop, while during a fallow period soil fertility can be recreated with a fraction of R.

---

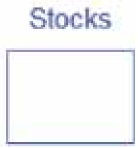
[3] Version 9 and beyond has 4 layers:
- Interface Layer which contain input output relationship
- Map layer: to layout your thinking in the front of a map
- Model Construction Layer; where you construct the model can be simulated, it is often refered to as the
- Equation Layer; to view list of all equation of model elements and relations

Constructing a model

- Make sure you are in the second layer. You will notice a globe (world) icon underneath the arrow at the top left hand corner. On the top you will see 14 icons, starting with 'box' icon at the furthest left and 'ghost' at the furthest right.
- Make a variable of soil fertility. To do this, click on the box icon then click again anywhere on the empty space. Change the name from 'Noname1' into 'Soil Fertility' or any variable name you like. There are no restriction on length. What you have just made is called building blocks.

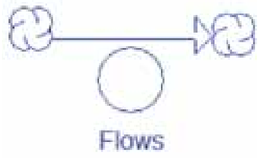
STELLA has 4 types of building box:

1. Stocks



Stocks are accumulations. They collect whatever flows into and out of them

2. Flows

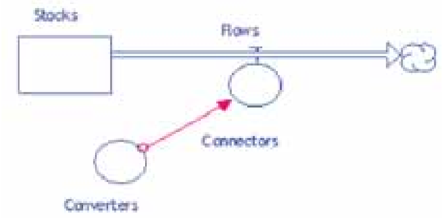


The job of flows is to fill and drain accumulation s. The unfilled arrow head on the flow pipe indicated the direction of the flow.

3. Converters

The converter serves a practical and handy role. It holds values for constants, defines external inputs to the model, calculates algebraic relationships and serves as the repository for graphical functions. In general it converts inputs into outputs.

4. Connectors



The job of the connector is to connect model elements.

This is an example of how building blocks are used.

Constructing a model (Continued.)

- Since 'Soil Fertility' will decrease during cropping year, you will have to make an outflow from 'Soil Fertility'. Name the flow as 'Depletion'.
- 'Depletion' depend on depleting factor (D), length of cropping year **and length of fallow year** (if it is a fallow year, depletion will not occur). Make 3 converters and name them as D, TimeCrop and TimeFallow. Connect all 3 converters to 'Depletion'
- Now you will need to define the relationship between those parameters into an equation in 'Depletion'. See what happen if you click twice on 'Depletion'.
- Click Cancel and see what happen if you click on the globe icon then clicking twice on 'Depletion'.
- You are now in equation box. Type out the following equation:

IF(MOD(TIME[4], (TimeCrop+TimeFallow)) <TimeCrop) THEN (Soil_Fertility*D) ELSE(0)1

Make sure there is a connection from 'Soil Fertility' to 'Depletion'

- You will see that all building blocks except 'Depletion' has question mark on them. They are asking for a value. Put the following value just for a try out. D=0.4, Soil fertility=10, TimeFallow=3, TimeCrop=3
- Now, do the same step for recreation factor, which is an inflow to 'Soil Fertility'. What do you think should be the equation in 'Recreation'? First try a constant value, for example put IF(MOD(TIME, (TimeCrop+TimeFallow)) > TimeCrop)THEN(0.2) ELSE(0)
- The Trenbath model used a 'saturation' function in which the recreation depends on the difference between current fertility and a maximum value (Finf), modified by a 'half-recovery time' Kfert, so we make converters for Finf (value e.g. 10) and Kfert (value e.g. 5): IF(MOD(TIME, (TimeCrop+TimeFallow)) >TimeCrop)THEN((Finf Soil_Fertility)*Soil_Fertility/(Finf-Soil_Fertility+Kfert*Finf)) ELSE(0)
- Now go to the third layer. You will now see the values and equations of your model.

Making an Output

- To make a graph click on graph icon (7th icon from left) and click again anywhere. A box named untitled graph will emerge.
- Click twice on the graph then select 'Soil Fertility' from Allowable Box. Click the arrow pointing to the right. Then click OK.
- You may do the same thing with table icon (8th icon from left)

Running the Program

- To run the program choose **Run** from Run Menu. You can also run the program by pressing **Ctrl-R** or clicking the running-man icon in the bottom left hand corner then click an arrow pointing to the right.
- To see the simulation result, click twice on the graph or table.
- You will notice that the simulation run until time 12 with Delta Time (DT)=0.25. You can change this by choosing **Time Spec** on Run Menu. Try putting DT=1 and length simulation to 50.
- Run the model again and see what happen.
- Try changing R and D value. At what value would they result in stable condition?

---

[4] MOD(TIME,(TimeCrop+TimeFallow)) will give current time minus the already completed cycles. The early part of a new cycle is cropped, the latter part is fallow.

Sensitivity Analysis

STELLA has a sensitivity analysis option. Let's try to see how sensitive 'Soil fertility' to changes in 'Depletion'

- Choose **Sensi Spec** from Run Menu. Choose D from Allowable Box then click an arrow pointing to right.
- Click D on Selected Box, then fill the following value: Start=0.2, End=0.6. Click on **Set** then **OK**.
- Click twice on graph, then choose graph type as Comparative.
- Now Run the model and see the result.

Exercises

The model you have built is very simple. Now try adding other variables to add complexity into it. Below are several exercises you may like to try out.

- Add crop production into it. Assume crop production is linearly proportional to decreased in 'soil fertility'/depletion. Find the total crop production during simulation.
- Assume that in the sum of cropping time and fallow time is a constant over time (a constant cycle). Fallow time is a function of total cumulative production. If the cumulative production meet a certain target then continue with the same length of fallow time. If cumulative production below target you need to shortened the length of fallow time to make up for.
- Assume target production as a function of population density and food needed per capita

Appendix 2. User's guide to WaNuLCAS

Introduction

This user's guide is designed to help users in working with **WaNuLCAS** model. Throughout this document, we assumed users have a basic experience on using software under Microsoft Windows.

To be able to run WaNuLCAS reasonably well the recommended system requirements are:

- Pentium processor or better
- Microsoft Windows^{TM} 95
- 64 MB RAM
- VGA display of at least 256 colors

There are three options for running WaNuLCAS:

1. Under STELLA demo, you can
    a. change most of the parameter values within the ranges set
    b. run the model and explore the result
2. Under STELLA Commercial Run Time (CRT), which is a 'stripped' version of Stella Research. You can:
    a. run the model
    b. change most of the parameter values within the ranges set (directly or by copying from EXCEL files), and
    c. save/save as to maintain modified parameters
    d. save graphs as pictures for printer
3. Under STELLA Research. In addition to the above you can also:
    a. modify parameters ('constant') not included in the input lists
    b. modify the parameter ranges
    c. save output tables as text files for further data handling with other software
    d. create new graphs or tables
    e. print a listing of all program equations
    f. modify the layout of the model
    g. modify equations, add or delete pools and flows, i.e. modify 'the model itself'.

If you do any modification, please keep track of changes made for any future report on your 'modified WaNuLCAS'.

This document deals with the second option that is running WaNuLCAS in Stella Regular/Research version. A free downloadable version of Stella is available at **http://www.iseesystems.com/**. All option available except saving a file.

Installing WaNuLCAS

You may copy and decompress the WaNuLCAS model (WaNuLCAS.stm) and the MS Excel file (Wanulcas.xls) into any directory.

Starting WaNuLCAS

Initiate Excel. Open Wanulcas.xls. The Wanulcas.xls file contains a number of macros. The default setting in most MS Windows and MS Excel installations is to not allow such macros and to not even ask whether the user wants them or not. If your computer security settings don't allow any macro to run, you may need to change the security level for macros.

If you are working with MS Excel 2003, to change the security level go to "Tools" and "Macro" and choose "low", then close and re-open Wanulcas.xls. It will give a warning that the file contains a macro. Choose "enable macro".

If you working with MS Excel 2007, to change the security level for macros, follow the diagram below. This is to make sure the macro built to ease inputting parameters in the model is working properly.

The Trust Center contains security and privacy settings. These settings help keep your computer secure. [illegible] do not change these settings.

○ Disable all macros except digitally signed macros

● Enable all macros (not recommended; potentially dangerous code can run)

Then run STELLA, it will automatically open a blank working model. Close it then open WaNuLCAS.stm from appropriate directory.

If you are working with STELLA 7 or 8, to update the linked input from Wanulcas.xls into WaNuLCAS.stm, click "Yes" when the question, "This model contain links. Re-establish link?", appears on your screen when you open WaNuLCAS.stm. Be sure that you already have EXCEL running in the background and Wanulcas.xls have already been opened.

STELLA only allows the changes to occur when both Excel and STELLA files are open simultaneously. Changes made in Excel prior to establishing the link will not change parameter values in STELLA. To overcome this problem we have built an updating macro in Excel. Run this macro by pressing Ctrl-U, Ctrl-W, Ctrl-W after you have the link between STELLA and Excel file establish to make sure all the input parameters value in STELLA model corresponds to the value in Excel.

If you working with STELLA 9, to update the linked input from Wanulcas.xls into GenRiver.stm use the "ImportData" option under the "Edit" menu. There are two types of importing data: the first one is import data “one time”, meaning the data is imported without establishing a link; the second is “persistent” data import, meaning the data is imported and a link established.

Most of the contents of Wanulcas.xls are linked to WaNuLCAS model as input parameters. Linking enable you to change input value in WaNuLCAS by changing associated values in Wanulcas.xls. The linked values are marked by blue font.

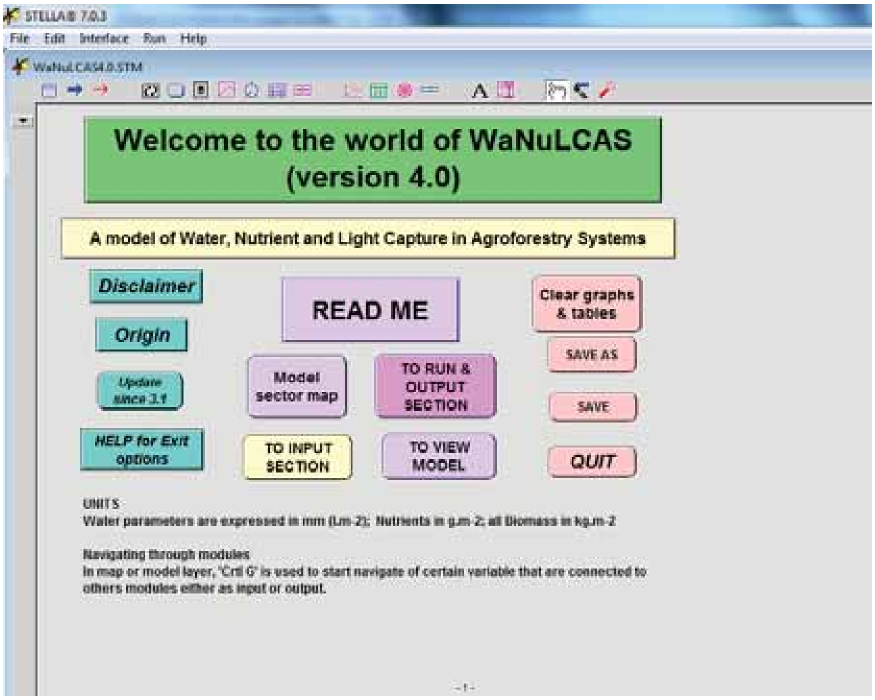
To cross-check whether input parameters were updated both in MS Excel and Stella, open a table in STELLA, tabulate input parameters and compare them with the MS Excel file.

File name

If you working with STELLA 7 or 8, the active link between the MS Excel file Wanulcas.xls and the STELLA file WaNuLCAS.stm requires that the filename for the Excel file remains the same. If you want to differentiate multiple versions of the input parameters, please make separate copies in different subdirectories (folders), otherwise the links are lost.

If you working with STELLA 9, you can give any name for the Wanulcas.xls.

You are now inside the **Main Menu** of WaNuLCAS and ready to work! In your screen you will see something like Figure App2.1.



UNITS
Water parameters are expressed in mm (Lm-2); Nutrients in g.m-2; all Biomass in kg.m-2

Navigating through modules
In map or model layer, 'Crtl G' is used to start navigate of certain variable that are connected to others modules either as input or output.

Figure App2.1. View of WaNuLCAS **Main Menu**

To familiarize yourself with WaNuLCAS we suggest you to try the following exercise:

- First, view the model then return to **Main Menu**
- Second, run the model using default parameters, then look into the simulation result
- Third, check nitrogen, phosphorus, carbon and water input-output summary of model
- Fourth, modify input parameters and try new run
- Fifth, import output resulting from new run

In the following sections you will find description on how to perform each of the suggested exercise.

To view model

This option will give you a bird's eye view of model structure: sectors, pools, flows and influences (see Figure below). Using STELLA Research you can modify the model at this level.

To return to **Main Menu** you may click on the available button or click on an arrow pointing upwards in the top left corner.

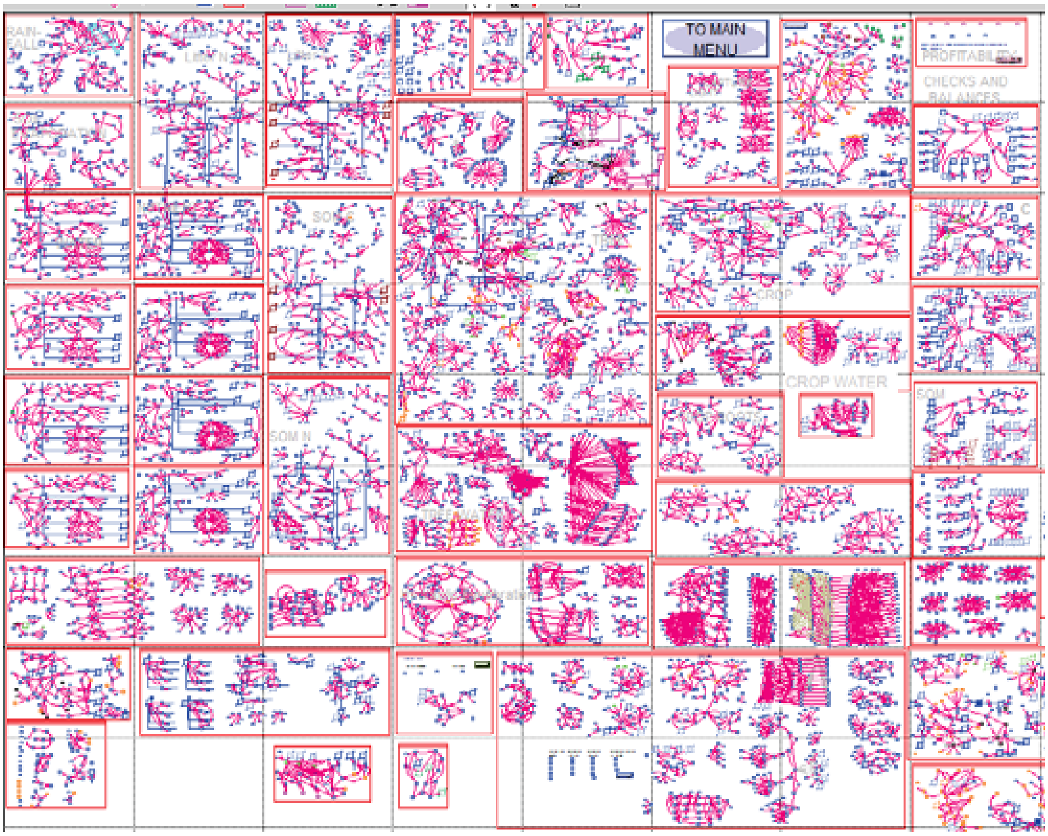


Figure App2.2. A bird's eye view of WaNuLCAS

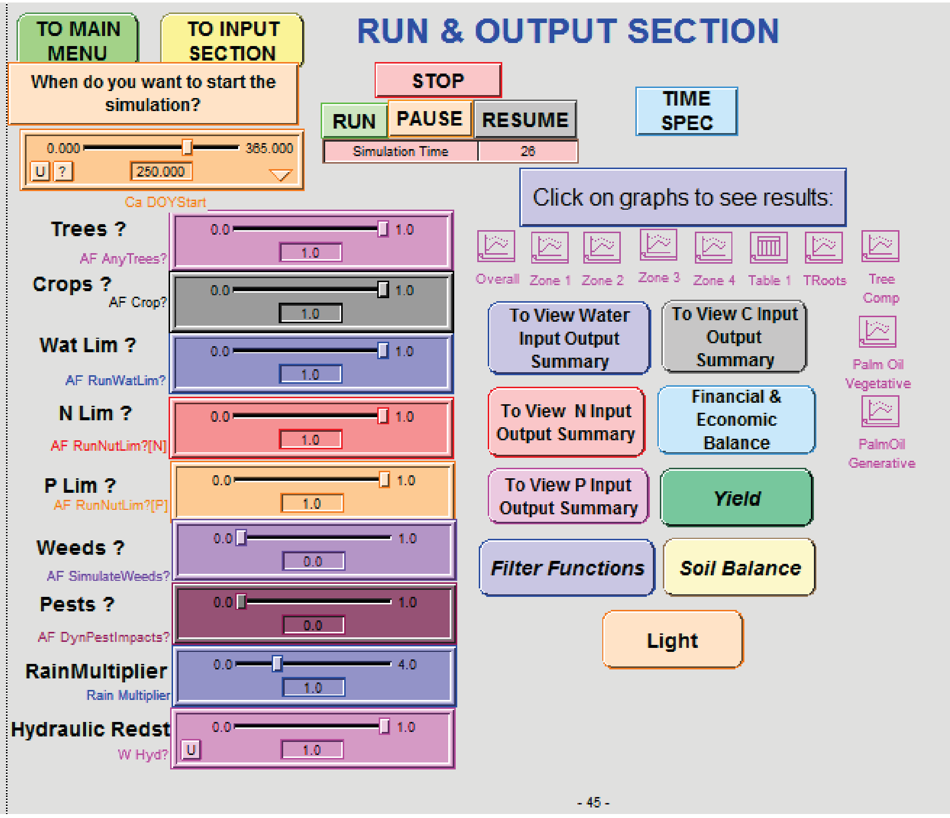
To run and see simulations results

To run or to see simulation result from **Main Menu** click on **TO RUN AND OUTPUT SECTION** button.

Running WaNuLCAS

On the output screen you will find 5 buttons which control simulation run as listed below.

Buttons	Purpose
Run	To start simulation
Pause	To pause during simulation run
Stop	To stop simulation
Resume	To resume simulation after pausing
Time Spec	To specify length of simulation time



When do you want to start the simulation?

Ca DOYStart: 0.000 – 365.000, 250.000

Simulation Time 28

Click on graphs to see results:

Trees ? AF AnyTrees? 0.0 – 1.0, 1.0

Crops ? AF Crop? 0.0 – 1.0, 1.0

Wat Lim ? AF RunWatLim? 0.0 – 1.0, 1.0

N Lim ? AF RunNutLim?[N] 0.0 – 1.0, 1.0

P Lim ? AF RunNutLim?[P] 0.0 – 1.0, 1.0

Weeds ? AF SimulateWeeds? 0.0 – 1.0, 0.0

Pests ? AF DynPestImpacts? 0.0 – 1.0, 0.0

RainMultiplier Rain Multiplier 0.0 – 4.0, 1.0

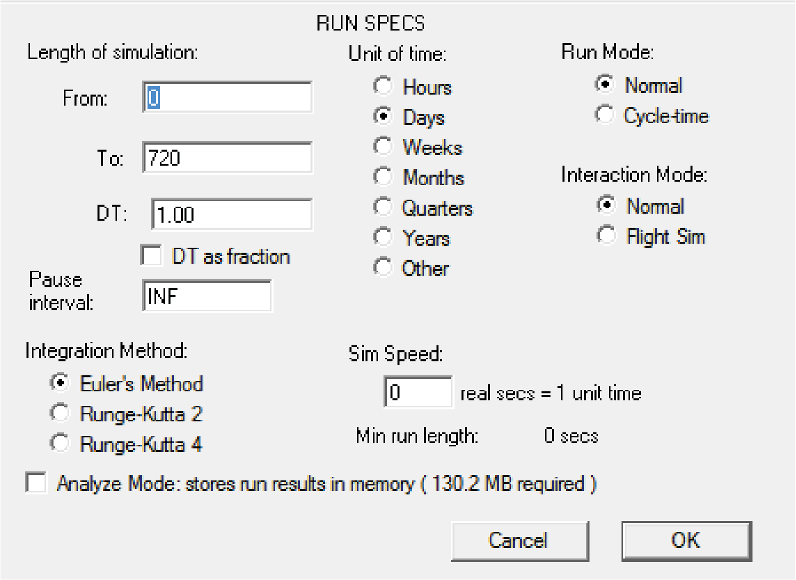
Hydraulic Redst W Hyd? 0.0 – 1.0, 1.0

- 45 -

Figure App2.3. View of Output Section

Below the running control buttons, you will see a box displaying time lapsed since start of simulation (see Figure App2.3).

There are 9 sliders to simplify running different type of simulations. See Appendix 7 on acronyms to know more of the function of these sliders. The *Time Specs* screen will appear (Figure App2.4) allowing you to change beginning and ending period of simulation, also DT which is incremental time of simulation. We strongly advise you to keep DT value at 1.



RUN SPECS

Length of simulation:
From: 0
To: 720
DT: 1.00
☐ DT as fraction
Pause interval: INF

Unit of time:
○ Hours
● Days
○ Weeks
○ Months
○ Quarters
○ Years
○ Other

Run Mode:
● Normal
○ Cycle-time

Interaction Mode:
● Normal
○ Flight Sim

Integration Method:
● Euler's Method
○ Runge-Kutta 2
○ Runge-Kutta 4

Sim Speed:
0 real secs = 1 unit time
Min run length: 0 secs

☐ Analyze Mode: stores run results in memory (130.2 MB required)

Figure App2.4. View of Time Specification screen

Seeing simulation result

There are two types of output result, (A) Graphs and (B) Tables.
To view a graph/table, click twice on the graph icon. What you will see is actually a stack of graphs/tables. To view the rest of graphs, click on the folded page at the bottom left corner.

When you look at graphs, notice that the scale on Y axis between parameters on the same graph can be different. Match the index number of parameters with index number of scales in Y axis.

Listed below is summary of available output on display. More detailed descriptions on output parameters are listed in Appendix 4 of this document.

A. Graphs

Overall : Summaries of overall zones and specific output related to Tree

Output	Content	Graph Type
Page 1	Plant biomass, tree biomass presence as total biomass	Time series
Page 2	Distribution of rainfall	Time series
Page 3	Distribution of cumulative amount of water drained out	Time series
Page 4-5	Distribution of cumulative amount of nutrient leached out	Time series
Page 6	Cumulative plant water uptake	Time series
Page 7	Total plant N & P uptake per day	Time series
Page 8-9	Amount of nutrient presence in plant aboveground biomass	Time series
Page 10	Water available, demanded and taken up by tree per day	Time series
Page 11-12	Nutrient available, demanded and taken up by tree per day	Time series
Page 13-15	Factors limiting tree growth	Time series
Page 16	C and Nutrient in SOM + litter pool	Time series
Page 17	Tree biomass and diameter	Time series
Page 18	Plant biomass, tree biomass presence as leaf and twig biomass	Time series
Page 19	Tree canopy biomass and cumulative pruned biomass	Time series
Page 20	Plant (Leaf and Twig) biomass	Histogram
Page 21	Water stock	Histogram
Page 22 - 23	Nutrient stock	Histogram
Page 24 - 25	Pore volume	Histogram

Zone 1, Zone 2, Zone 3, and Zone 4 : Each of these graphs contain similar output parameter related to zone 1, 2, 3 and 4

Output	Content
Page 1	Factors limiting crop growth
Page 2	Distribution of water stock
Page 3-4	Distribution of nutrient in soil
Page 5	Distribution of crop water uptake
Page 6	Distribution of tree water uptake
Page 7,9	Distribution of crop nutrient uptake
Page 8,10	Distribution of tree nutrient uptake
Page 11-12	Nutrient available, demanded and taken up by crop per day

OilPalms: spesific output for oilpalm

Output	Content
Page 1-3	Fruit biomass
Page 4	Biomass and oil harvested

Tree comp: spesific output related to the tree phenology

Output	Content
Page 1	Tree Leaf Area Index (LAI)

B. Tables

There is only one table containing 2 pages of water balance, plant biomass, water, N and SOM in soil.

Adding additional output parameters

To add more parameters to your tables or graphs do the following:

- Click twice on your graph/table. After a graph/table appear, click twice again on it. Now, you will see a box emerge with 2 small boxes in the upper section. The left box contains parameters that can be loaded into graph/table. The right box contains parameters already in the graph/table. A graph can contain up to 5 parameters while a table can contain more than 40 parameters.
- To load a parameter into the graph/table, highlight the parameter in **allowable** box then click an adjacent arrow pointing to the right.
- If you want to load a parameter to a new clean page, prior to the above you need to click an arrow pointing upward at the bottom left corner pointing (adjacent to **Page**). Keep on clicking until you see **NEW** as page number.

Locking graphs or tables to speed your simulation

You can lock pages in your graphs and tables that you do not need. Locked graphs or tables will not be updated in the next simulation run. This would save a lot of time needed to run the model. To lock graph or table click on the lock icon. It is in the bottom left corner of your graph or on the top right corner of your table.

Printing your output

You can print your output by clicking on printer icon. It is in the bottom left corner of your graph or on the top right corner of your table. It will ask you to specify which page of your graph or table you want to print.

Importing output results

You can save your table as a text file and your graph as a pct file. You can also use copy (Ctrl-C) and paste (Ctrl-V) your output table. For graphs you can use screen dump (Shift-Print) then paste to your favourite Microsoft software.

To view input-output summary

To view input-output summary, click on button **TO RUN & OUTPUT SECTION** in the **Main Menu**. There are 7 input-output summary you can see, Water, Nitrogen, Phosphorus, Carbon, Financial & Economic, Yield, Filter functions, Soil and Light. Choose the relevant one.
This screen gives you summary of input and output in the current system simulated.   A list of parameters acronym found in this section is shown in **Appendix 4** under **Balance**.

To Modify Input Parameters

Click on button '**TO INPUT SECTION**' from **Main Menu**.   It will lead you to list of input parameters.

Click again on button associated with specific parameters. Refer to Appendix 7 in Documentation Manual for more detailed information on input parameters.

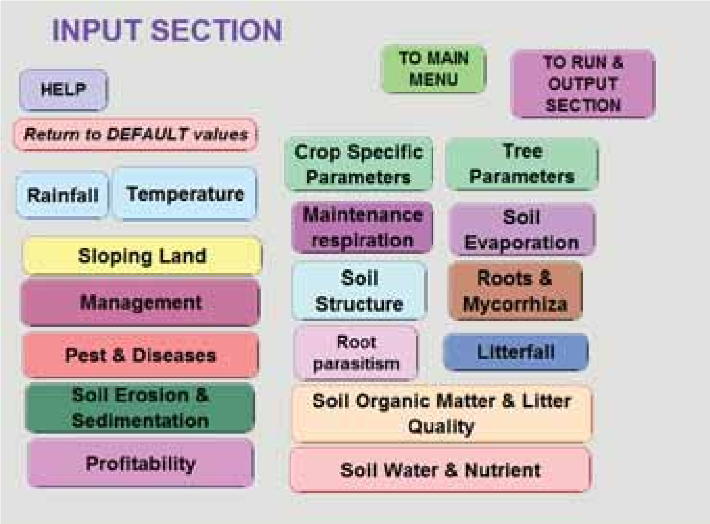


Figure App2.5. View of input menu

Basically data for WaNuLCAS model are placed in two locations, (1) the upper layer of the model and (2) Wanulcas.xls. When you click on input parameter button, it will either take to the actual input parameter location or inform you to enter it through Wanulcas.xls.

From upper layer of model there are basically three types of input device used, (1) list, (2) sliders and (3) graphical input

Changing Input Values

To modify input value just write over the current value. It will change if the new input value is within allowable range. If not, the maximum or minimum in the range will replace the value specified.

To check allowable value, please refer to Appendix 7 in documentation manual. If you experience problems, please let us know.

Please refer to **STELLA** Technical Manual to change input values on specific input device.

Description of Input on Wanulcas.xls

This Excel file is contains data used as input parameters and routines to help users in generating these input parameters. To be able to open the file you need at least Excel ver. 5.0 (MSOffice 97). The Excel must have Visual Basic Application as add-in working. The descriptions of each sheet are listed below and see Appendix 3 for more detail explanation.

All the sheets are protected by default in such a way that you will still be able to change input parameters. You can unprotect the sheets using password wanulcas (all lower case).

All input parameters in Wanulcas.xls are linked to WaNuLCAS model. For these parameters you should change it directly from the Excel sheet. For more detail description, please see Appendix 3.

Sheet	Content
READ ME	General information
Pedotransfer	Program to generate soil hydraulic properties. Output generated from this program forms data input for WaNuLCAS. These can automatically be copied to the sheet 'SOIL HYDRAULIC' where it is linked to WANuLCAS model.
Soil Hydraulic	Soil Hydraulic input parameters for each soil layer and zone. Linked to WaNuLCAS STELLA model
Phosphorus	Program to generate K_a (adsorption constant) of P, based on double Langmuir equation and related P_Bray to total mobile soil P content
Weather	Daily rainfall, daily soil temperature and daily potential evaporation
Slash and Burn	Slashing schedule and parameter impacts on the burning event
Crop Parameters/Library	Crop specific parameters
Tree Parameters/Library	Tree specific parameters
Crop Management	Planting schedule, fertilization schedule
Tree Management	Tree planting & timber harvesting schedule and pruning management.
Pedo SOM	Bulk density pedotransfer and Soil Organic Matter pedotransfer
Profitability	Input prices and labour requirement for the agroforestry system simulated and output produced.
Julian day	Information to converting calendar days per month into the 'day-of-year' (DOY) or 'Julian days' format used in the stella model
Link output	Information on how to make proper link between Wanulcas.xls and WaNuLCAS.stm and examples output that can get from WaNuLCAS simulation

To make Changes in the Model

There are 2 levels of model changes you can do; (1) change a constant parameter into a dynamic variable and (2) adding additional influencing parameter /factor to existing equations.

Changing a constant into dynamic variable

You can do this by making a constant parameter depends on existing-state variable.For example: change biomass-to-height conversion factor (Cq_HBiomConv[Cr]) into crop stage (Cq_Stage) dependent.

Adding influencing factor to existing equations

You can do this by adding additional parameter to existing equations. For example: add effect of slope as a parameter influencing potential evaporation (Evap_Pot).

Appendix 3. Description on Excel files accompanying WaNuLCAS model

The WaNuLCAS model is accompanied by 2 excel file; Wanulcas.xls and TreeParameterization.xls. Wanulcas.xls contains input parameters and routines to generate input parameters. The input parameters are linked to WaNuLCAS model. See table in Appendix 2, page 143 for short descriptions of Wanulcas.xls content. TreeParameterization.xls is developed to generate input parameters for tree. There are several other help files to assist users in generating input parameters as well as better understand WaNuLCAS model. See our web page for more information.

Wanulcas.xls

The basic purpose of this Excel file is to ease users in modifying input parameters needed to run WaNuLCAS model. Input parameters in this file are linked to the model (in the WaNuLCAS.stm file).

There are two ways to change input parameters in excel, making sure changes also occur inside the model:

1. Change input values in excel ONLY if you run the model and excel simultaneously with links established, or
2. Change input values in excel before hand then save the file. When you run the model and establish links with excel later, make sure you press Ctrl-U, Ctrl-Y or Ctrl W. This is an updating macro built within this file, that re-activates the links and sends the current parameter values of the excel file to their counterparts in stella. The macro activated by Ctrl-U will update crop and tree parameters, the Ctrl-Y will update the soil and Ctrl W will update climate parameters.

Below are comprehensive explanation of each sheet and the relevant WaNuLCAS input parameters are tabulated. Refer to Appendix 7 for definition of acronyms.

READ ME sheet.

This is the main menu of Wanulcas.xls. It contains general information and button commands to browse other sheets.

AF System sheet

This sheet stores design of the system simulated includes tree density, tree spacing, tree position within zone and zone width.

WEATHER sheet

This sheet stores daily data for 3 weather components in WaNuLCAS: Rainfall, Soil Temperature and Potential Evaporation. Default length of data and links are 1 year (365 days). These data are linked.

WaNuLCAS input parameters	Location
Rain_Data	cells C5 – C369
Temp_DailyData	cells D5 – D369
Temp_DailyPotEvap	cells E5 – E369

Pedotransfer sheet

The 'Pedotransfer' sheet contains calculation tools to help generating tables of soil hydraulic parameters. The routine is based from Wosten *et al*. (1998).

You will need to enter 5 input parameters for basic soil properties in the 'Input' section of this sheet. The pedotransfer function then estimates the parameters of a Van Genuchten equation and tabulates the relations between soil water content, hydraulic conductivity and pressure head.

The saturated hydraulic conductivity K_{sat} generated in this equation is used as a default value, representing a soil with little structure and macroporosity. The model will use the KsatInit value that you specify yourself – if it differs from the default value it is possible to simulate a gradual collapse of soil structure (with a rate governed by S_KStructDecay, set at 0.001); macroporosity can be re-created by 'Worm' activity (see Section 3.3.6).

In WaNuLCAS two definitions of 'field capacity' are used to determine the maximum soil water content one day after a rainfall event:

- Fieldcap1 = the soil water content (found in cell O11) at which downward drainage will become less then a small value K_{crit} (set in cell B36 of the input section, e.g.. 0.1 cm d^{-1}), and
- Fieldcap2 = the soil water content that is in hydrostatic equilibrium with a water table at a distance defined from the bottom of layer 4 (default distance is 0). This second value is calculated inside the STELLA model.

For the actual calculations the highest of these two values for any cell is used. The results generated by the pedotransfer routine are found in the 'Output' section of this sheet. These generated values are input parameters for WaNuLCAS model.

WaNuLCAS input parameters	Location in Excel
W_PhiTheta	cells N13 – N64
W_Ptheta	cells O13 – O64
W_PhiP (this is linked to 4 tables in the stella: W_PhiPH, W_PhiPMH, W_PhiPML, W_PhiP)	cells R13 – R64
W_ThetaPMax, W_ThetaP	cells U13 – U64
KsatDflt (default value, endpoint of loss of soil structure)	N11
Ksat (value used to initializa the model)	M11
Field Capacity1 (conductivity-limited)	O11

These input parameters need to be copied to the sheet 'Soil Hydraulic' properties. To copy the parameters for soil layer *i* and zone *j*, fill in *i* and *j* in cell N8 and N9 then click on the **COPY** button. Along with the above parameters value, input on soil texture and bulk density will be copied as well as input for Soil Organic Matter module and Soil Erosion module.

You can set up the model with the same properties for all zones and layers by repeating this for *i* = 1...4 and *j* = 1...4, modify the properties by layer or use different properties for any of the 16 cells.

Phosphorus sheet

The 'Phosphorus' sheet contains a procedure to calculate Ka_P, the apparent P adsorption constant as a function of the P concentration and P availability indices such as the P_Bray value. To run this, click on button **Psorption isotherm & Soil Database**. In this section you need to fill in the soil type for each layer of your soil in cells M8...M11. We provide default values for 9 soil types, as listed in U12....U20 If you have your own data, you can fill in parameters of a single or two-term Langmuir isotherm to describe your soil type. The parameters currently used for each soil layer are found in cells N8...R11. You also have to specify the bulk density of each layer (it is possible to use a value here that differs from the one used in the pedotransfer sheet...).

The parameters of the Langmuitr sorption isotherm are used to derive values of Ka_P for each layer, tabulated in the '**P Sorption Output**' section of the worksheet These values are linked to the WaNuLCAS.stm model.

This sheet also includes a section to initialize P in each cell (zone * layer), on the basis of indices of P availability such as the P_Bray value. To do this, you first have to specify two properties of the P availability index: the volume ratio of soil to solution used during the extraction, and the relative sorption affinity in the extraction medium (at the temperature and other conditions used). For two methods we provide these parameters P-water (compare De Willigen and Van Noordwijk, 1987) and P-Bray (with a tentative, poorly tested estimate of the relative sorption affinity of 2% of the original value).

Once the method has been thus defined, click on '**Initial P Soil**' and fill in the initial P soil indices for each cell (AD8...AG11). The values will be converted to amount of soil P in the units expected in WaNuLCAS.stm in cells (AD14...AG17). These converted values are linked to the Stella model.

WaNuLCAS input parameters	Location in Excel
Initial P in soil, N_Init*i*[P,Zone]; *i* = 1, .., 4	cells AC14 – AF17
N_KaPDef[Layer]	cells C93 – C143, E93 – E143, G93 – G143, I934 – I143

Nitrogen

This sheet store initial soil Nitrogen for each soil layer and zone.

Slash&Burn sheet

This sheet holds input parameters related to impacts of slash and burn on soil as a function of increased temperature at the soil surface. The values in this sheet is the current default values in the model, but are not linked to the model. To modify, you will need to copy the modification you have made in this sheet, to a graph converter inside the model (see from INPUT SECTION button in the model).

WaNuLCAS input parameters	Location
S&B_SurfLitBurnFrac	cells B12 – B26
S&B_NecroBurnFrac	cells C12 – C26
S&B_DeadWoodBurnFrac	cells D12 – D26
S&B_AerosolFrac	cells E12 – E26
S&B_NvolatFrac	cells F12 – F26
S&B_PvolatFrac	cells G12 – G26
S&B_SOMBurnFrac	cells J12 – J19
S&B_FirMortSeedBank	cells K12 – K19
S&B_FirIndPMobiliz	cells L12 – L19
S&B_FirImpPSorption	cells O12 – O26

CROP MANAGEMENT sheet

This sheet holds a schedule for planting crops (by zone and type) and applying N or P fertilizers. The current simulation year is defined as **YEAR 0**.

In this sheet you will be able to define the type of crop you plan to use in the simulation. In cell B2-F2 fill the letter code of crop type associated with the code in the database. It is written as options on the left hand side or see sheet **CROP LIBRARY**. The type of crop you choose here determine the parameter values copied to sheet **CROP PARAMETERS** and **PROFITABILITY**, where the values are linked to model.

You have a maximum of 5 different crop type to grow in one simulation. The letter code you fill in here will be converted to crop type value of 1 to 5, which you will use as input parameter in **column D, I, N and S**.

WaNuLCAS input parameters	Location
S&B_SurfLitBurnFrac	cells B12 – B26
S&B_NecroBurnFrac	cells C12 – C26
S&B_DeadWoodBurnFrac	cells D12 – D26
S&B_AerosolFrac	cells E12 – E26
S&B_NvolatFrac	cells F12 – F26
S&B_PvolatFrac	cells G12 – G26
S&B_SOMBurnFrac	cells J12 – J19
S&B_FirMortSeedBank	cells K12 – K19
S&B_FirIndPMobiliz	cells L12 – L19
S&B_FirImpPSorption	cells O12 – O26

CROP LIBRARY sheet

This sheet holds a database for crop specific parameters and crop related input-output for the system simulated. Overall there are 58 input parameters including 5 growth parameters as a function of crop stage. Some parameters are only required for specific settings in the simulation, e.g. there are three mutually exclusive ways of determining root length density in each cell in each time step, as governed by C_RootType.

Currently there are 10 possible type of crops in the database. For 5 of them we have provided default values, that is for crop **Cassava**, **Maize**, **Upland Rice**, **Groundnut** and **Cowpea**. If you have your own data you can fill your data values under crop type **Yours1**, ..., **Yours5**. For the whole list of input parameters stored, please refer directly to the excel sheet.

To choose the type of crop you use in simulation fill in relevant cell in sheet **CROP MANAGEMENT**.

TREE MANAGEMENT sheet

This sheet holds a schedule for tree planting, pruning and timber harvesting. As in **CROP MANAGEMENT** the current simulation year is defined as **YEAR 0**.

This where you define the type of tree you plan to use in the simulation. In cell E4-G4 fill the letter code of tree type associated with the code in the database. It is written as options on the left hand side or see sheet **TREE LIBRARY**. The type of crop you choose here determine the parameter values copied to sheet **TREE PARAMETERS** and **PROFITABILITY**, where the values are linked to model.

It is possible to grow 3 different tree type simulteneously.

WaNuLCAS input parameters	Location
T_PlantY[Tree]	cells C11 – C31, E11 – E31, G11 – G31
T_PlantDoY[Tree]	cells D11 – D31, F11 – F31, H11 – H31
T_PrunY	cells K11 – K51
T_PrunDoY	cells L11 – L51
T_PrunFracD[Tree]	cells M11 – M51, O11 – O51, Q11 – Q51
T_PrunHarvFracD[Tree]	cells N11 – N51, P11 – P51, R11 – R51
T_WoodHarvY[Tree]	cells C37 – C57, E37 – E57, G37 – G57
T_WoodHarvDoY[Tree]	cells D37 – D57, F37 – F57, H37 – H57
S&B_FirIndPMobiliz	cells L12 – L19
S&B_FirImpPSorption	cells O12 – O26

TREE PARAMETERS sheet

This sheet holds tree specific parameters. There are 95 input parameters. As in crop specific parameters, some inputs are only required if you run certain type of simulations.

All you need to fill in this sheet is the letter code of tree type (cell E8 - G9) associated with the code in the database. You have a maximum of 3 different tree type grow simultaneously in one simulation. The tree type you fill in is link to **PROFITABILITY** sheet

In the database we have so far provided only 2 default values for the trees Gliricidia sepium and Peltophorum dasyrrachis. If you have your own data you can fill in this value into the database (see cell L6). For the whole list of input parameters stored, please refer directly to the excel sheet.

PROFITABILITY sheet

The sheet contains input needed in the simulated systems and output produced. There are basically 3 categories of input, for the whole field, trees and crops. Input for the whole field you will need to fill in this sheet, while for plant input it is filled in database **TREE/CROP LIBRARY**. See directly in the excel sheet the whole list of input parameters.

Soil Hydraulic sheet

This sheet contains soil hydraulic input parameters as generated and copied from Pedotransfer sheet. The cells here are linked to the WaNuLCAS model. There are no user inputs required here, as all input is generated by the pedotransfer sheet. You can, however, check that the COPY command has lead to the expected results or not.

Pedo_SOM sheet

This sheet provide users a way to parameterize Soil Organic Matter module. This worksheet, based largely from pedotransfer equations, can be used to generate $C_{organic}/C_{reference}$ value and to derive S_BDBDRefDecay value. $C_{organic}/C_{reference}$ is a ratio between actual $C_{organic}$ measured in the field with a reference $C_{organic}$ value for forest top soils of the same texture and pH.. This value can be used as an indicator of how soil organic matter had changed over the years at the current site. This value is an input parameter to initialize soil organic matter using Methods 2 (see Soil Organic Matter module).

S_BDBDRefDecay is parameter value indicating the rate of soil bulk density compaction over time. This changes could be due to management or soil structure degradation. The new sheet helps to calculate BDBDRef value, that is the ratio between measure soil bulk density with a reference value of bulk density at the same $C_{organic}$ content. There are two types of reference values, at agriculture soils and at forest soils (BDBDRef1 and BDBDRef2). Using these two ratio values we can have a first indication on what would be a reasonable value of S_BDBDRefDecay.

Tree parameterization.xls

This file for generate input parameters in tree library in Wanulcas.xls. Below are the detail explanation for each sheet carried out.
Main sheet, this sheet is the main menu of tree parameterization.xls which is conducted in to two parts tree survey and FBA model. Tree survey is more for estimate the tree specific

parameter while FBA model for estimate allometric branching for WaNuLCAS. It contains general information and button commands to browse tree survey and FBA model.

Survey sheet, this sheet contains 39 question that split in to 10 categories, growth stage, growth, canopy, light capture, rain interception, tree water, N fixation, N and P concentration, litterfall and litterquality. Users may answer all questions or only some of those related to the certain category.

WaNuLCAS sheet, while user answer the question on sheet survey, the input parameter for Wanulcas.xls (tree library sheet) will be automatically estimated on this sheet, later user can copy the result from this sheet to the tree library sheet.

WanFBA sheet, all input that needed to run FBA model are prepared on this sheet based on the observational data in the field. The input are needed split in to 4 categories, information of branching pattern, information of tree size, information of woody part and information of final links.

Input sheet, when user had finished fill in all the information, with ‘Ctrl H’ will be automatically estimated all input that needed to run the FBA model on this sheet, and ‘Ctrl R’ will be automatically estimated biomass allometric equation for each part (total biomass, wood, leaf and twig and litterfall). The biomass allometric equation will be automatically copied on sheet WaNuLCAS.

Sumoutput sheet, the sumoutput shows not only allometric equation but also all the important information that can be obtained from this program.

Estimate sheet, this sheet contains estimate input for WanFBA input compared to the default value.

FBA.xls

Fractal braching analysis.xls is a tool that help user to generate allometric equation of tree based on non-destructive approach using generic from $Y = a D^b$, Y = tree biomass and D = tree diameter.

Rainfall simulator.xls

Rainfall simulator is tool to generate daily rainfall simulator based on common ‘Markov chain’ way, which basically consists of two steps: i) simulating rainfall occurrence, i.e. determining whether or not a day is a rainy day or not, and ii) for rainy days, determine the amount of rainfall. A number of parameter inputs such as peakiness of the season, number of wet day, relative wet persistence, weibull value, etc is needed to generate daily rainfall using this tool. ‘Help file rainfall simulator’ is a file that help user to generate those input parameters. Daily or monthly rainfall data are the basis data to generate those inputs.

Appendix 4. List of Output Acronyms and Definition

No.	Acronym	Definition
1.	AF	"Agroforestry Zone" – overall design on the system
2.	B	Balance (carbon=BC, nutrient=BN, BS=Soil or water=BW)
3.	C	Crop (C = Crop, C_N = Crop Nutrient or CW = Crop Water)
4.	E	Erosion
5.	Light	Light
6.	P	Profitability (economic sector of the model)
7.	Rain	Rain
8.	T	Tree (T = Tree, T_N = Tree Nutrient or TW = Tree Water)
9.	TF	Oil palm

No.	Acronym	Definition	Units	Location
1.	AF_DepthLay1	Initial soil thickness in layer 1	m	Soil Balance
2.	BT_HarvCum[DW,Tree]	Cumulative biomass harvested from each type of tree	kg m^{-2}	Yield
3.	BC_ChangStock	Changes of current carbon stock and initial over duration of the simulation	g m^{-2}	Carbon Balance
4.	BC_CO2FromBurn	Cumulative amount of carbon released into air from burning event	g m^{-2}	Carbon Balance
5.	BC_CPhotosynth	Amount of carbon produced by crop through photosynthesis	g m^{-2}	Carbon Balance
6.	BC_CRespforFix	Amount of carbon released by crop due to respiration needed for N fixation	g m^{-2}	Carbon Balance
7.	BC_Crop	Amount of carbon currently presence as crop biomass	g m^{-2}	Carbon Balance
8.	BC_CropInit	Initial amount of carbon presence as crop biomass	g m^{-2}	Carbon Balance
9.	BC_CStockInit	Initial amount of carbon in soil organic matter and surface litter pools and tree	g m^{-2}	Carbon Balance
10.	BC_CurrentCStock	Current amount of carbon in soil organic matter, surface litter pools, tree, crop, necromass and weed	g m^{-2}	Carbon Balance
11.	BC_ExtOrgInput	Amount of carbon in external organic input eg. mulch	g m^{-2}	Carbon Balance
12.	BC_GWEffect_CO2_eq_g_per_m2	Net global warming effect in g CO_2 equivalent per m^2 over duration of the simulation	g m^{-2}	Carbon Balance
13.	BC_HarvestedC	Amount of carbon in harvested crop/yield (average over total field length)	g m^{-2}	Carbon Balance
14.	BC_HarvestedT	Amount of carbon in harvested component of tree	g m^{-2}	Carbon Balance

No.	Acronym	Definition	Units	Location
15.	BC_Inflows	Total amount of carbon entered the systems through tree and crop photosynthesis, initial tree and crop biomass and weed	g m^{-2}	Carbon Balance
16.	BC_NecromassC	Amount of carbon as necromass	g m^{-2}	Carbon Balance
17.	BC_NetBal	Balance value for carbon. It is used to check model calculation and should be (virtually) 0	g m^{-2}	Carbon Balance
18.	BC_Outflows	Current amount of carbon losses from the system through crop harvested, component of tree harvested and carbon respired	g m^{-2}	Carbon Balance
19.	BC_SOM	Current amount of carbon in soil organic matter and surface litter pools	g m^{-2}	Carbon Balance, Graph Overall (16)
20.	BC_SOMInit	Initial amount of carbon in soil organic matter and surface litter pools	g m^{-2}	Carbon Balance
21.	BC_TimeAvgCStock	Total amount of carbon in the whole system averaged over the simulation period	g m^{-2}	Carbon Balance
22.	BC_TotalRespired	Total carbon respired	g m^{-2}	Carbon Balance
23.	BC_TPhotosynth	Amount of carbon produced by tree through photosynthesis	g m^{-2}	Carbon Balance
24.	BC_Tree	Current amount of carbon in tree biomass	g m^{-2}	Carbon Balance
25.	BC_TreeInitTot	Total amount of carbon initialized as tree biomass	g m^{-2}	Carbon Balance
26.	BC_TRespforFix	Amount of carbon released by crop resulted from respiration for N fixation	g m^{-2}	Carbon Balance
27.	BC_Weed	Amount of carbon currently presence as weed	g m^{-2}	Carbon Balance
28.	BC_WeedSeeds	Amount of carbon as seeds of weed	g m^{-2}	Carbon Balance
29.	BN_CBiomInit[SlNut]	Initial amount of nutrient in crop biomass	g m^{-2}	N Balance, P Balance
30.	BN_CHarvCum[SlNut]	Amount of nutrient in harvested crop/yield (average over whole field)	g m^{-2}	N Balance, P Balance
31.	BN_CNdfaFrac	Fraction of N derived from fixation by all crop	dimensionless	Yield
32.	BN_CNFixCum	Total amount of N fixed by crop	g m^{-2}	N Balance
33.	BN_CropBiom[SlNut]	Current amount of nutrient (N or P) in crop biomass (average over total field length)	g m^{-2}	Graph Overall (8 – 9)
34.	BN_CropBiom[SlNut]	Current amount of nutrient in tree biomass	g m^{-2}	N Balance, P Balance, Graph Overall, (8 – 9)
35.	BN_CUptTot[SlNut]	Total amount of nutrient taken up by crop (average over total field length)	g m^{-2}	Graph Overall, (7)
36.	BN_EffluxTot[SlNut]	Current amount of nutrient loss from the system through crop harvested, leaching, surface run off, etc	g m^{-2}	N Balance

No.	Acronym	Definition	Units	Location
37.	BN_ExtOrgInputs[SlNut]	Total amount of nutrient entered the system from external organic input	g m^{-2}	N Balance, P Balance
38.	BN_FertCum[SlNut]	Cumulative amount of fertilizer input (average over total field length)	g m^{-2}	N Balance, P Balance
39.	BN_Immob[SlNut]	Current amount of nutrient in immobile pool	g m^{-2}	N Balance, P Balance
40.	BN_ImmPool[SlNut]	Initial amount nutrient in immobile pool	g m^{-2}	N Balance, P Balance
41.	BN_InfluxTot[SlNut]	Total amount of nutrient entered the system from initial crop biomass, fertilizer, external organic input, etc	g m^{-2}	N Balance
42.	BN_LatInCum[SlNut]	Nutrient input due to lateral flow	g m^{-2}	N Balance, P Balance
43.	BN_LatOutCum[SlNut]	Amount nutrient flows out due to lateral flow	g m^{-2}	N Balance, P Balance
44.	BN_LeachingTot[SlNut]	Total amount of nutrient leached out from bottom layers (average over total field length)	g m^{-2}	N Balance, P Balance
45.	BN_Lit[SlNut]	Current amount of nutrient in litter layer	g m^{-2}	N Balance, P Balance
46.	BN_LitInit[SlNut]	Initial amount of nutrient in litter layer	g m^{-2}	N Balance, P Balance
47.	BN_NetBal[SlNut]	Balance value for nutrient. It is used to check model calculation and should be (virtually) 0	g m^{-2}	N Balance, P Balance
48.	BN_NutVolatCum[SlNut]	Total amount of carbon volatilized from burnt necromass	g m^{-2}	N Balance, P Balance
49.	BN_SOM[SlNut]	Current amount of nutrient in soil organic matter pool	g m^{-2}	N Balance, P Balance, Graph Overall (16)
50.	BN_SOMInit[SlNut]	Initial amount of nutrient in soil organic matter pool	g m^{-2}	N Balance, P Balance
51.	BN_StockInit[SlNut]	Initial amount of nutrient (average over all zones and layers)	g m^{-2}	N Balance, P Balance
52.	BN_StockTotInit[SlNut]	Total amount of initial soil nutrient	g m^{-2}	N Balance, P Balance
53.	BN_StockTot[SlNut]	Currentl amount of nutrient in soil (average over all zones and layers)	g m^{-2}	N Balance, P Balance
54.	BN_THarvCumAll[SlNut]	Amount of nutrient in biomass harvested from tree (average over total field length)	g m^{-2}	N Balance, P Balance
55.	BN_TNdfaFrac	Fraction of N derived from fixation by tree	dimensionless	Yield
56.	BN_TNFixAmountCum	Total amount of N fixed by crop	g m^{-2}	N Balance
57.	BN_TreeInit[SlNut]	Initial amount of nutrient in tree biomass	g m^{-2}	N Balance, P Balance
58.	BN_WeedBiom[SlNut]	Current amount of nutrient in weed biomass	g m^{-2}	N Balance, P Balance
59.	BN_WeedSeedBank[SlNut]	Current amount of nutrient in seedbank	g m^{-2}	N Balance, P Balance

No.	Acronym	Definition	Units	Location
60.	BN_WeedSeedInit[SlNut]	Initial amount of nutrient in seedbank	g m^{-2}	N Balance, P Balance
61.	BS_SoilCurr	Current amount of soil	kg m^{-2}	Soil Balance
62.	BS_SoilDelta	Overall balance of input and output of soil in the model. A value of 0 means that the model calculation is in balance.	kg m^{-2}	Soil Balance
63.	BS_SoilInflowcum	Total amount of soil inflow	kg m^{-2}	Soil Balance
64.	BS_SoilInit	Initial amount of soil	kg m^{-2}	Soil Balance
65.	BS_SoilLossCum	Total amount of soil loss	kg m^{-2}	Soil Balance
66.	BW_DrainCumV	Total amount of water draining (average over all zones and layers)	l m^{-2}	Water Balance
67.	BW_EvapCum	Total amount of water evaporates from soil surface (average over all zones and layers)	l m^{-2}	Water Balance
68.	BW_LatInCum	Amount of lateral inflow (subsurface) of water	l m^{-2}	Water Balance
69.	BW_LatOutCum	Amount of lateral outflow (subsurface) of water	l m^{-2}	Water Balance, Graph Overall (3)
70.	BW_NetBal	Overall balance of input and output of water in the model. A value of 0 means that the model calculation is in balance.	l m^{-2}	Water Balance, Graph Overall (10)
71.	BW_RunOffCum	Amount of (surface) run off water	l m^{-2}	Water Balance
72.	BW_RunOnCum	Amount of (surface) run on water	l m^{-2}	Water Balance
73.	BW_StockInit	Initial total amount of water in all layers and zones of soil	l m^{-2}	Water Balance
74.	BW_StockTot	Current total amount of water in soil profile	l m^{-2}	Water Balance
75.	BW_UptCCum	Cumulative amount of water uptake by crop	l m^{-2}	Water Balance, Graph Overall (6)
76.	BW_UptTCum[Tree]	Cumulative water uptake by each tree	l m^{-2}	Water Balance Graph Overall (6)
77.	C_AgronYields[Crop]	Agronomic yield for each type of crop	kg m^{-2}	Yield
78.	C_Biom[Zone,DW]	Current crop biomass in each zone (including canopy, storage, roots)	kg m^{-2}	Graph Overall (1), Graph Zonei (1)
79.	C_BiomCan[Zone,DW]	Current crop canopy biomass in each zone	kg m^{-2}	Graph Overall (18)
80.	C_FracLim[LimFac]	Average value over the simulation for each limiting factor for crop growth, value between 0 and 1	-	Yield

No.	Acronym	Definition	Units	Location
81.	C_HydEqFluxes[Zone]	Flux of crop water by hydraulic lift	mm	Water Balance
82.	C_NDemand[Zone]	Amount of nutrient demanded by crop in each zone	kg m^{-2}	Graph Zone*i* (11 – 12)
83.	C_NPosGro[Zone,SlNut]	The effect of nutrient stress on crop growth (0=no growth, 1=no stress)	dimensionless	Graph Zonei (1)
84.	C_NUptPot[Zone]	Amount of nutrient available for crop uptake in each zone	g m^{-2}	Graph Zonei (11 – 12)
85.	C_NUptTot[Zone]	Amount of nutrient uptake by crop in each zone	g m^{-2} day^{-1}	Graph Zonei (11 – 12)
86.	Cent_BalTotal[SlNut]	Overall balance of input and output in minera¬lization module (adapted from CENTURY model). A value of 0 means that model calculations are in balance	g m^{-2}	N Balance, P Balance
87.	CW_PosGro[Zone]	The effect of water stress on crop growth in each zone (0=no growth, 1=no stress)	dimensionless	Graph Zone*i* (1)
88.	E_TopSoilDepthAct[Zone]	Current soil thickness in layer 1	m	Soil Balance
89.	GHG_CumCH4Emission	Cumulative emission of CH_4	g m^{-2}	N Balance
90.	GHG_GWP_N2O&CH4	Global Warming Potential of the systems based on the emmsion of CH_4 and NO_2. It is expressed relative to CO_2	-	N Balance
91.	GHG_N2_Fraction	Fraction of N_2 emission	dimensionless	N Balance
92.	GHG_NO_Fraction	Fraction of NO emission	dimensionless	N Balance
93.	GHG_N2O_Fraction	Fraction of N_2O emission	dimensionless	N Balance
94.	Light_CRelCap[Zone]	Relative light capture by crop (on scale 0-1)	g m^{-2}	Graph Zone*i* (1)
95.	Light_CRelSupply[Zone]	Potential crop growth limited by light capture relative to the potential without presence of trees (1 = no limitation, 0 = no growth)	-	Light
96.	N_CumAtmInput[SlNut]	Amount of nutrient derived from atmospheric deposition	g m^{-2}	N Balance, P Balance
97.	N_CUpti[Zone,SlNut]	Amount of nutrient uptake by crop from i-th soil layer of each zone per day	g m^{-2} day^{-1}	Graph Zone*i* (7, 9)
98.	N_EdgeFFH[SlNut]	A value describing filter function horizontally at the edge of plot	dimensionless	Filter Function
99.	N_EdgeFFV[SlNut]	A value describing filter function vertically at the edge of plot	dimensionless	Filter Function
100.	N_LeachCumV[Zone,SlNut]	Total amount of nutrient leached out from bottom layer of each zone	g m^{-2}	Graph Overall (4 – 5)
101.	N_Leachi[Zone,SlNut]	Amount of nutrient leached out from i-th layer of each zone	g m^{-2}	Graph Zone*i* (13 – 14)
102.	N_LocFF3i[SlNut]	A value describing filter function in the 3rd layer of soil	dimensionless	Filter Function
103.	N_Stocki[Zone,SlNut]	Amount of nutrient stock in each zone of layer *i*	g m^{-2}	Graph Zone*i*(3, 4)

No.	Acronym	Definition	Units	Location
104.	N_TotFFTot[SlNut]	A value describing how the whole system function as a filter. Filter function defined as nutrient taken up by plant divided by total nutrient taken up and loss	dimensionless	Filter Function
105.	N_TUpti[Zone,SlNut]	Amount of nutrient taken up by tree from *i*-th soil layer of each zone per day	g m^{-2} day^{-1}	Graph Zone*i* (8, 10)
106.	P_CCostAvg[Price]	Average cost of crop management	currency unit ha^{-1}	Economic & Financial Balance
107.	P_CReturnAvg[Price]	Amount of money contributed from crop production	currency unit ha^{-1}	Economic & Financial Balance, Yield
108.	P_CumLabUse	Total amount of labour use to manage the system	man days	Yield
109.	P_GeneralCost[Price]	Total cost needed to maintain the system	currency unit ha^{-1}	Economic & Financial Balance
110.	P_NPV[Price]	Net present value of the system	currency unit ha^{-1}	Economic and Financial Balance
111.	P_TCostTot[Price]	Total cost of crop management	currency unit ha^{-1}	Economic and Financial Balance
112.	P_TReturn[Price]	Amount of money contributed from tree production	currency unit ha^{-1}	Yield
113.	P_TReturnTot[Price]	Total amount of money contributed from tree production	currency unit ha^{-1}	Economic and Financial Balance, Yield
114.	Rain	Amount of rain per day	l m^{-2} day^{-1}	Graph Overall (2)
115.	Rain_Cum	Cumulative amount of rainfall	l m^{-2}	Water Balance, Table 1 (1)
116.	Rain_In[Zone]	Actual amount of rain going into each zone	l m^{-2} day^{-1}	Graph Overall (2), Table 1 (1)
117.	Rain_IntercEvapCum	Amount of water evaporated from intercepted water	l m^{-2}	Water Balance
118.	T_Biom[Tree]	Current amount of biomass for each tree (above and belowground)	kg m^{-2}	Graph Overall (1)
119.	T_BiomCumTot	Total cumulative amount of tree biomass (including litterfall, rootdecay, harvested pruning)	kg m^{-2}	Yield
120.	T_CumLatexHarv[Tree]	Total latex harvested	kg m^{-2}	Yield
121.	T_FracLim[Tree,LimFrac]	Average value over the simulation for each limiting factor for tree growth, value between 0 and 1	dimensionless	Yield

No.	Acronym	Definition	Units	Location
122.	T_FruitHarvCum[Tree]	Total fruit harvested	kg m^{-2}	Yield
123.	T_GroRes[Tree]	Current amount of biomass in tree growth reserves	kg m^{-2}	Graph Overall (17)
124.	T_HydEqFluxes[Tree]	Flux of tree water by hydraulic lift	mm	Water Balance
125.	T_LAI[Tree]	Tree Leaf Area Index	dimensionless	Graph Tree Comp
126.	T_LfTwig[Tree]	Current amount of biomass in tree canopy	kg m^{-2}	Graph Overall (17, 18, 19)
127.	T_Light[Tree]	Fraction of light received by tree	dimensionless	Graph Overall (13 – 15)
128.	T_NBiom[SlNut,Tree]	Current amount of nutrient in tree aboveground biomass	g m^{-2}	N Balance, P Balance, Graph Overall (8 – 9)
129.	T_NDemandAll[SlNut]	Amount of nutrient demanded by tree per day	g m^{-2} day^{-1}	Graph Overall (11 – 12)
130.	T_NfixCum[SlNut,Tree]	Cumulative amount of nutrient derived from fixation by tree	g m^{-2}	N Balance
131.	T_NPosgro[SlNut]	The effect of nutrient stress on tree growth (0=no growth, 1=no stress)	dimensionless	Graph Overall (13 – 15)
132.	T_NUptPotAll[SlNut]	Total amount of nutrient in all soil layers available for tree per day	g m^{-2} day^{-1}	Graph Overall (11 – 12)
133.	T_NUptTotAll[SlNut]	Total amount of nutrient taken up by tree (average over total field length)	g m^{-2} day^{-1}	Graph Overall (7,11 – 12)
134.	T_Root[Tree]	Current amount of tree root biomass	kg m^{-2}	Graph Overall (17)
135.	T_StemDMax	Stem diameter of tree	m	Graph Overall (17)
136.	T_Wood	Current wood/stem biomass	kg m^{-2}	Graph Overall (17)
137.	T_WoodHarvCum[Tree]	Total timber/wood harvested	kg m^{-2}	Yield
138.	TF_BunchWeight[Tree,FruitBunch]	Total weight of oil palm fruit per fruit stages	kg m^{-2}	Graph OilPalm
139.	TF_CumFruitHarv[Tree]	Cumulative amount of oil palm fruit harvested	kg m^{-2}	Graph OilPalm
140.	TF_CumOilHarvest[Tree]	Cumulative amount of oil harvested	kg m^{-2}	Graph OilPalm
141.	TF_FemBunchFrac[Tree]	Fraction of female flowers/fruit	kg m^{-2}	Graph OilPalm
142.	TF_ FruitperBunch[Tree,FruitBunch]	Number of oil palm fruit per fruit stages	kg m^{-2}	Graph OilPalm

No.	Acronym	Definition	Units	Location
143.	TF_WatNutSuff[Tree]	The effect of water and nutrient stress on the oilpalm growth	dimensionless	Graph OilPalm
144.	TW_DemandActAll	Amount of water demanded by all tree per day	l m^{-2} day^{-1}	Graph Overall (10)
145.	TW_Posgro[Tree]	The effect of water stress on tree growth (0=no growth, 1=no stress)	dimensionless	Graph Overall (10, 13 – 15)
146.	TW_UptPotAll	Total amount of water in all soil layers available for tree per day	l m^{-2} day^{-1}	Graph Overall (10)
147.	TW_UptTotAll	Current amount of water uptake by tree from all soil layers per day	l m^{-2} day^{-1}	Graph Overall (10)
148.	W_CUpti[Zone]	Amount of water taken up by crop from i-th soil layer of each zone per day	l m^{-2} day^{-1}	Graph Zonei (5)
149.	W_DrainCumV[Zone]	Cumulative amount of water drained out from bottom layer	l m^{-2}	Graph Overall (3)
150.	W_Stocki[Zone]	Amount of water each zone in i-th soil layer	l m^{-2}	Graph Zonei (2)
151.	W_TUpti[Zone]	Amount of water taken up by all tree from i-th soil layer of each zone per day	l m^{-2} day^{-1}	Graph Zonei (6)

Appendix 5.Deriving uptake equation (P. de Willigen)

According to De Willigen and Van Noordwijk (1987 - Table 9.1, equ. 12.9) uptake rate is given by:

$$\frac{\rho^2 \Theta \beta}{2\phi\eta} = \frac{(\rho^2 - 1)\bar{c}}{2G(\rho)} \qquad \textbf{[A1]}$$

Now (l.c. page 125):

$$G(\rho) = \frac{1}{2}\left\{\frac{1-3\rho^2}{4} + \frac{\rho^4 \ln \rho}{\rho^2 - 1}\right\} \qquad \textbf{[A2]}$$

As normally ρ « 1

$$G(\rho) \approx \rho^2 \left(-\frac{3}{8} + \frac{1}{2}\ln \rho\right) \qquad \textbf{[A3]}$$

The parameters ρ1, ϕ2 and η3 are given by:

$$\begin{aligned} \rho &= \frac{R_1}{R_0} && 1 \\ \phi &= \frac{D \quad S_i}{U\,R_0} = \frac{D\theta\beta C_i}{U\,R_0} && 2 \\ \eta &= \frac{H}{R_0} && 3 \end{aligned} \qquad \textbf{[A4]}$$

and the dimensionless concentration by:

$$\bar{c} = \frac{C}{C_i} \qquad \textbf{[A5]}$$

where D is the diffusion coefficient ($m^2.d^{-1}$), H is the thickness of the soil layer (m), *U* is the uptake rate ($g.m^{-2}.d^{-1}$), R_0 the radius of the root (m) and R_1 the radius of the soil cylinder surrounding the root. The latter is given by:

$$R_1 = \frac{1}{\sqrt{\pi L_{rv}}} \qquad \textbf{[A6]}$$

The parameter 4 denotes the buffer power of the soil. Substitution of (A2)-(A6) into (A1) leads to:

$$U = \frac{D\bar{C}H}{R_1^2\left(-\frac{3}{8} + \frac{1}{2}\ln \rho\right)} \qquad \textbf{[A7]}$$

The diffusion coefficient is a function of the water content Θ5, according to:

$$D = (a_1\Theta + a_0)\ \Theta\ D_0 \qquad \textbf{[A8]}$$

where D_0 is the diffusion coefficient of the nutrient in question in water, whereas the concentration can be calculated from the amount in the layer N_{stock} (g.m^{-2}):

$$C = \frac{N_{stock}}{K_a + \Theta} \qquad \textbf{[A9]}$$

K_a being the adsorption constant. Substitution of (A2)-(A9) into (A1) ultimately yields (A10) which is the basis for equation (10) in WaNuLCAS.

$$U = \frac{\pi D_0\ (a_1\Theta + a_0)\ \Theta\ H\ N_{stock}}{(K_a + \Theta)\left[-\frac{3}{8} + \frac{1}{2}\ln\left\{\frac{1}{R_0\ \sqrt{\pi L_{rv}}}\right\}\right]} \qquad \textbf{[A10]}$$

Appendix 6. Trouble-shooting and Tips

As for any complex system, the number of ways in which the model can go wrong is nearly infinite, while there is only one (or a few) ways it can go right., So the odds certainly are against us. If things go wrong, however, there are a number of ways to identify the source of the errors as a step towards mending it.

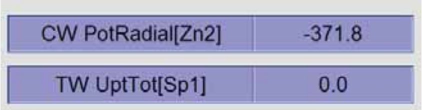
Difficulties in loading the files:

- **Links can not be established**: check whether you have indeed opened the right XLS file and have not changed the position of any of the linked parameters by adding or deleting rows or columns or moving cell contents around,
- **Low Memory ('cannot continue DDE conversation')**; it may help to remove all memory demanding programs, including net-work links and microsoft office toolbars from the memory; sometimes it helps to re-boot the computer and start afresh; this type of error message may occur when you update the links by running the Ctrl+Y, Ctrl+W or Ctrl+U macro in the excel; if the problem persists you'll have to get more RAM on your computer (32 MB is a bare minimum); you can also make runs in the Stella model without opening the excel + links, or close the excel file after updating parameter values, to increase the memory allocation for the Stella model.
- **Running speed** can be increased by locking graphs/tables that you're not currently interested in.
- **Links are not working**; Wanulcas.xls is developed using MS Excel with English language as the settings. If you use MS Excel with settings on other languages the link will not work. This is because the links will use different language term. As an example: in English language setting, position of a cell is referred to as R (Row) and C (Column)olumn. In Portuguesse, it is referred to as L (Lina) and C (Colom). Similarly, in French it refer to as L and C. If you are working using STELLA version 6 or above, you can modify the links directly within the model (WaNuLCAS.stm) using Link Editor option. If you are working with Stella version 5, you will need to update the links again.

Error message at start or during RUN

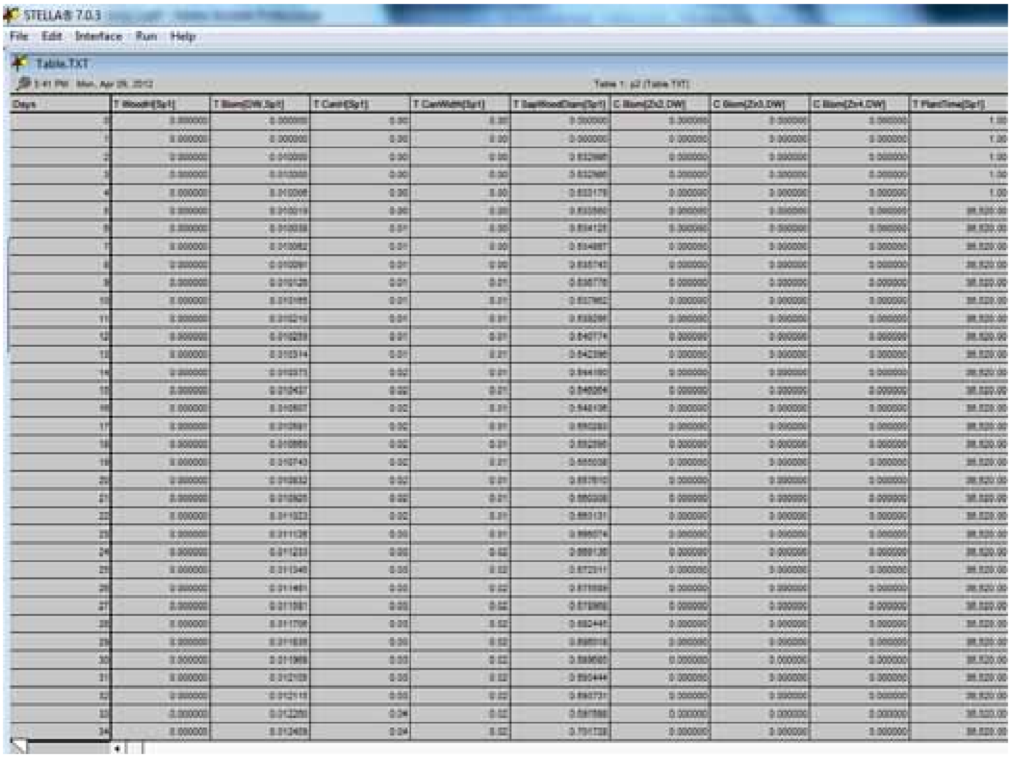
It is possible that when you press RUN you get an error message, in stead of output. The message will indicate a parameter name and the error usually consists of division by zero. We have tried to protect all equations from such an event, but if necessary you can add an 'If *** <> 0 then '...existing equation...' else 0' statement to the equation involved, with the *** replaced by any divisor in the equation.

The current value of all parameters and variables at the time of the crash can be viewed by inserting a numeric display output as a step towards identifying what goes wrong. Below is an example.



```
CW PotRadial[Zn2]   -371.8
TW UptTot[Sp1]      0.0
```

If the RUN actually starts, a Table can be used to view more then one parameter at a time, and check its changes with time.



A second class of error is that trees or crops do not grow as expected, or trees or crops do not grow at all

A second class of error is that trees or crops do not grow as expected, or other events do not happen as you though you asked for in the calendar. In such case you can add a new table to the output screen and check where the error originates by tabulating output values related to the event. For trees and crops it is helpful to tabulate the growth stage as well as components of the biomass, to check whether the error is in the plants not getting started at all, or not making biomass. It may be necessary to tabulate input values and compare with the values you intended.

Sometimes the x-axis for tabulated input parameters, such as the strings of crop or tree parameter, gets changed and all parameter values are shifted by one or more positions, leading to nonsensical results; if this happens open the graph and re-adjust the number of points.

You can try the ‘return to default’ button on the ‘input’ screen to restore (unintentional) modifications of parameter settings that may be responsible for unexpected run results; if you want to modify the ‘default’ values to which you return with this button, you have to modify the values in the dialogue boxes on the ‘second level’ (the modeling layer))

Appendix 7.Input parameters and their definition

Abbreviations used in parameter names

No	Acronym	Definition	No	Acronym	Definition
1.	AF	"Agroforestry Zone" – overall design of the system	14.	Mn	Nutrients in Litter Layer
2.	C	Crop (C = Crop, C_N = Crop Nutrient or CW = Crop Water)	15.	Mn2	Nutrients in Soil Organic Matter (SOM)
3.	Ca	Crop Calendar (schedule)	16.	N	Nutrient (currently including N and P)
4.	Cent	Input Output Summary for Litter (based on Century Model)	17.	P	Profitability (economic sector of the model)
5.	Cent2	Input Output Summary for SOM (based on Century Model)	18.	PD	Pest and Disease
6.	Cq	Crop Sequence (crop parameters)	19.	Rain	Rain
7.	E	Erosion	20.	Rt	Root
8.	Evap	Evaporation	21.	S&B	Slash and Burn
9.	G	Grazing	22.	S	Soil Structure
10.	LF	Lateral Flow	23.	T	Tree (T=Tree, T_N=Tree Nutrient or TW=Tree Water)
11.	Light	Light	24.	TF	Tree Fruit (oil Palm Module)
12.	Mc	Carbon in Litter Layer	25.	Temp	Temperature
13.	Mc2	Carbon in Soil Organic Matter (SOM)	26.	W	Water

Note: Without green dot are CORE modules, with '●' (green dot) in front means ADDITIONAL modules

No.	Acronym	Definition	Dimensions	Range of value (Default value)	Input Section (Link location in Excel)
1.	AF_AnyTrees?	Parameter governing an option to simulate system with trees. Value 0 means system without trees, value 1 means system with trees is possible	dimensionless	0 or 1 (1)	RUN & OUTPUT SECTION
2.	AF_Circ?	Switch to decide on circular versus linear symmetry. 1 = circular system, 0 =linear system	dimensionless	0 or 1 (0)	(AF System)
3.	AF_Crop?	Parameter governing an option to simulate system with crop. Value 0 means system without crop, value 1 means system with crop	dimensionless	0 or 1 (0)	RUN & OUTPUT SECTION
4.	AF_DeepSubSoil	Equivalent depth of the subsoil below layer 4, that is used to calculate the effective water outflow from the soil column, via S_KsatVDeepSub	m	0 - 10 (3)	Agroforestry Zone
● 5.	AF_DepthDynamic?	Swicth for making the depth of soil layer 1 on sloping land system a dynamic property	dimensionless	0 or 1 (0)	Agroforestry Zone/Sloping Land and Parkland System
6.	AF_DepthGroundWater Table	Depth of groundwater table below the bottom of layer 4, expressed in m. For the time being the value is used as a constant in defining 'field capacity'.	m	0 – 10 (0)	Agroforestry Zone
7.	AF_DepthLayi[Zone]	Soil depth increment in (= layer thickness of) *i*-th soil layer, *i* = 1, 2, 3, 4. For sloping land systems the value for the layer 1 is used as average topsoil depth at the start of the run; actual depth of layer 1 will be calculated from the two AF_Slope parameters	m	0 - 1 (.05, .15, .3, .5 for i = 1,..,4)	(AF System)
● 8.	AF_DynPestImpacts?	Switch governing an option to simulate system with dynamic pest impact. Value 0 means no dynamic pest impacts, value 1 means dynamic pest impacts is possible.	dimensionless	0 – 1 (0)	RUN & OUTPUT SECTION
● 9.	AF_PlotNumberUphill	Number of similar uphill plot neighbors as source of Lateral Inflow & Run-on	dimensionless	(0)	Agroforestry zone
10.	AF_RunNutLim[SoilNut]?	Switch governing an option to simulate system with nutrient limitation. Value 0 means no nutrient limitation, value 1 means nutrient is possible.	dimensionless	0 – 1 (1)	RUN & OUTPUT SECTION
● 11.	AF_RunOnFrac	Fraction of surface runoff from the area uphill that enters the simulation area as run-on.	dimensionless	0 – 1 (0)	Agroforestry Zone
12.	AF_RunWatLim?	Parameter governing an option to simulate system with water limitation. Value 0 means no water limitation, value 1 means water limitation is possible.	dimensionless	0 – 1 (1)	RUN & OUTPUT SECTION

No.	Acronym	Definition	Dimensions	Range of value (Default value)	Input Section (Link location in Excel)
13.	AF_SimulateWeeds?	Parameter governing an option to simulate weed growth. Value 0 means no weed growth, value 1 means weed will start growing whenever crop is absent.	%	0 or 1 (0)	RUN & OUTPUT SECTION
14.	AF_SlopeSurfInit	Slope (expressed as percent elevation increment per horizontal distance) of the soil surface at the start of the simulation; this value can differ from the slope of the soil profile AF_SlopeSoilHoriz, but should not differ too much.	%	0 – 100 (0)	Agroforestry Zone/Sloping Land and Parkland System
15.	AF_SlopeSoilHoriz	Slope (expressed as percent elevation increment per horizontal distance) of the soil horizons below the surface, especially that of the topsoil, used to calculate actual topsoil depth per zone.	%	0 – 100 (0)	Agroforestry Zone/Sloping Land and Parkland System
16.	AF_StoneFrac[Zone,SoilLayer]	Fraction of stone in each soil layer and zone	dimensionless	0 – 1 (0)	Agroforestry Zone
17.	AF_TreePosit[Tree]	Position of each tree type. It can be in zone 1 (1) or zone 4 (4); if one wants it to be in both, two otherwise equal tree types can be defined.	dimensionless	1 or 4 (1)	(AF System)
18.	AF_WeedZn?[Zone]	Switch 0 or 1 to have weeding application for each zone (1 = weeding application, 0 = no weeding)	dimensionless	0 or 1 (0)	Management/Weed Growth
19.	AF_Zone[Zone]	Width of each zone. Width of zone 4 is calculated back from AF_ZoneTot minus the sum of zone 1+2+3	m	0 – 100 (.5, 1,1)	(AF System)
20.	AF_ZoneTot	Total width of agroforestry system simulated	m	0 – 100 (3.5)	(AF System)
21.	C_AgronYMoistFrac[Cr]	Standard moisture content for expressing marketable yields of each crop	dimensionless	0 – 1 (.15)	(Crop Library)
22.	C_ApplyMaintResp?	On/Off switch for applying the maintenance respiration,;1 = on, 0 =off	dimensionless	0 or 1 (0)	Maintenance Respiration
23.	C_DailyWeedSeedDecayFrac	Fraction of the weed seed bank that looses viability and is transferred to the litter pool for decomposition	fraction day^{-1}	0 – 1 (.02)	Management/Weed Growth
24.	C_HostEffForT1[Cr]	Effectiveness of crop roots as host for a parasitic tree (T1)	cm^3 cm^{-1}	(0)	Root Parasitism
25.	C_RelRespGroRes	Relative weighting factor for growth used in calculating daily maintenance respiration	dimensionless	(.5)	Maintenance Respiration
26.	C_RelRespRt	Relative weighting factor for roots used in calculating daily maintenance respiration	dimensionless	(.3)	Maintenance Respiration
27.	C_RelRespStLv	Relative weighting factor for stem & leaves used in calculating daily maintenance respiration	dimensionless	(.5)	Maintenance Respiration

No.	Acronym	Definition	Dimensions	Range of value (Default value)	Input Section (Link location in Excel)
● 28.	C_RelRespYieldCurr	Relative weighting factor for developing fruits/Yield as part of total biomass as used for maintenance respiration	dimensionless	(1)	Maintenance Respiration
● 29.	C_ResidRemovalFrac	Fraction of crop residue removed from field (not returned as mulch). The same value applies for all zones and all crops used in the simulation	fraction	0 – 1 (0)	Management/Mulching
● 30.	C_RespperBiom	The relative use of resources for maintenance respiration per unit biomass	dimensionless	0 – 0.2 (.05)	Maintenance Respiration
● 31.	C_RespTemp	A graphical relation between temperature and maintenance respiration	dimensionless	(see C_RespTemp graph)	Maintenance Respiration
32.	C_Tmin	Minimum Air Temperature for Crop	0 Celsius	20	Temperature
33.	C_TOpt	Optimum Air Temperature for Crop	0 Celsius	21	Temperature
● 34.	C_WeedGermFrac	Fraction of weed seeds in the seed bank that germinates when a new opportunity arises, e.g. at the end of a cropping season	fraction	0 –1 (.1)	Management/Weed Growth
● 35.	C_WeedSeedBankInit	Initial dry weight of weed seeds in seed bank	kg m^{-2}	0 –1 (.01)	Management/Weed Growth
● 36.	C_WeedSeedExtInflux	Daily influx of weed seeds from outside of the plot	kg m^{-2} day^{-1}	0 – 0.1 (.00001)	Management/Weed Growth
37.	Ca_CType[Zone]	A graphical input parameter governing the type of crop planted in sequence, with the possibility of having different crops (and/or planting times) in different zones. Associated with type of crop in database. See Wanulcas.xls	dimensionless	1 – 5 (2)	(Crop Management)
38.	Ca_DoYStart	Day of year at which simulation starts	julian days	1 – 365 (300)	RUN & OUTPUT SECTION
39.	Ca_ExtOrgApp?[Type]	Parameter governing an option to have simulation with applying external organic input or not. Value 0 means not applying external organic input, value 1 means applying external organic input	dimensionless	0 or 1 (0)	(Crop Management)
40.	Ca_FertApp?[SiNut]	Parameter governing an option to have simulation with applying fertilizer or not. Value 0 means not applying fertilizer, value 1 means applying fertilizer	dimensionless	0 or 1 (1)	(Crop Management)
41.	Ca_FertOrExtOrgAppAmount[Zone]	Amount of N or P fertilizer or external organic applied. A graphical input parameter.	g m^{-2}	0 – 10 (4.5 for each N and P)	(Crop Management)

No.	Acronym	Definition	Dimensions	Range of value (Default value)	Input Section (Link location in Excel)
42.	Ca_FertOrExtOrgAppDoY[SiNut]	Time of fertilizer or external organic input application. A graphical input parameter.	julian days	1 – 365 (see excel sheet Crop Management)	(Crop Management)
43.	Ca_FertOrExtOrgAppYear[SiNut]	Year of fertilizer or external organic input application. A graphical input parameter.	dimensionless	any integer value (see excel sheet Crop Management)	(Crop Management)
44.	Ca_ImmAmount[P,Zone]	Amount of immobile P fertilizer applied. A graphical input parameter	g m^{-2}	(see Ca_ImmAmount graph)	Management/P Immobile Input
45.	Ca_ImmDOY[P]	Time of immobile P fertilizer application. A graphical input parameter	julian days	1 – 365 (see Ca_ImmDOY graph)	Management/P Immobile Input
46.	Ca_ImmY[P]	Year of immobile P fertilizer application. A graphical input parameter	dimensionless	Any integer value (see Ca_ImmY graph)	Management/P Immobile Input
47.	Ca_PlantDoY[Zone]	Day of crop planting for each subsequent crop. A graphical input parameter.	julian days	1 – 365 (see excel sheet Crop Management)	(Crop Management)
48.	Ca_PlantYear[Zone]	Year of planting for each subsequent crop. A graphical input parameter	dimensionless	any integer value (see excel sheet Crop Management)	(Crop Management)
49.	Cq_CHarvAlloc[Cr]	Allocation of biomass to harvested parts (grain, tuber) as a function of crop growth stage.	dimensionless	(see Cq_CHarvAlloc table)	(Crop Library)
50.	Cq_ClosedCan[Cr]	Amount of crop canopy biomass at which canopy is closed and nutrient demand per unit new biomass shifts from Cq_ConcYoung to Cq_ConcOld.	kg m^{-2}	0 – 0.5 (0.2)	(Crop Library/Nutrient Uptake)
51.	Cq_CLWR[Cr]	Crop leaf weight ratio = gram of green leaf area per gram of shoot, for each crop species as a function of crop growth stage.	g m^{-2}	(see Cq_CLWR table)	(Crop Library)
52.	Cq_ConcOld[Cr,SiNut]	Nutrient concentration in crop tissue formed after biomass has reached the Cq_ClosedCan value.	dimensionless	0 – 0.1 (N = .01, P = .0025	(Crop Library/Nutrient Uptake)
53.	Cq_ConcRt[Cr]	N concentration in crop roots	dimensionless	0 – 0.1 (.01)	(Crop Library/Nutrient Uptake)
54.	Cq_ConcYoung[Cr,SlNut]	Nutrient concentration in young crop biomass (before biomass has reached the Cq_ClosedCan value).	dimensionless	0– 0.1 (N = .015 P = .007)	(Crop Library/Nutrient Uptake)
55.	Cq_CovEff[Cr]	Crop Cover Efficiency factor, used in calculating erosion (Erosion type 1)	dimensionless	0 – 1 (1)	(Crop Library/Soil Erosion)

No.	Acronym	Definition	Dimensions	Range of value (Default value)	Input Section (Link location in Excel)
56.	Cq_CRelLUE[Cr]	Relative light use efficiency (fraction of Cq_GroMax achieved per unit light capture) for each type of crop grown as a function of crop growth stage.	dimensionless	(see Cq_CRelLUE table)	(Crop Library)
57.	Cq_DOYFlwBeg[Cr]	The earliest day in a year when crop start to flowers	julian days	1 – 365 (1)	(Crop Library/Annual or Perennial?)
58.	Cq_DOYFlwEnd[Cr]	The latest day in a year when crop start to flowers	julian days	1 – 365 (365)	(Crop Library/Annual or Perennial?)
59.	Cq_GroMax[Cr]	Maximum daily dry matter production rate at full light capture, for each crop species under local conditions	kg m^{-2} day^{-1}	0.001 – 0.1 (.014)	(Crop Library/Crop Growth)
60.	Cq_Gseed[Cr]	Seed weight (initial C_CarbHydrReserves to be used for growth).	kg m^{-2}	0.001 – 0.1 (.004)	(Crop Library/Crop Growth)
61.	Cq_HBiomConv[Cr]	Factor for conversion of crop biomass increment (up to crop stage 1) to crop height increment	dimensionless	0.1 – 10 (7)	(Crop Library/Crop Growth)
62.	Cq_kLight[Cr]	Light extinction coefficient for the crop canopy = efficiency of crop foliage in absorbing light.	dimensionless	0 – 1 (.65)	(Crop Library/Light Capture)
63.	Cq_LAIMax	Maximum leaf area index for the crop; if more biomass is produced a proportional amount is transferred to the litter layer	dimensionless	(5)	(Crop Library/Canopy)
64.	Cq_LignResid[Cr]	Lignin concentration of crop residue (eg. 20%=0.2).	dimensionless	0 – 1 (.2)	(Crop Library/Litter Quality)
65.	Cq_LignRootRes[Cr]	Lignin concentration of crop root residues	dimensionless	0 – 1 (.2)	(Crop Library/Litter Quality)
66.	Cq_Lp[Cr]	Hydraulic conductivity of crop roots, reflecting the physiological entry resistance to water per unit root length and unit gradient.	cm day^{-1}	0 – 0.00001 (.00001)	(Crop Library/Water Uptake)
67.	Cq_MaxRemob[Cr]	Maximum proportion of stem and leaves remobilized per day to the CarbHydrReserves pool, from which it can, for example, be used for growth of the storage component (grain, tuber)	day^{-1}	0 – 0.1 (.05)	(Crop Library/Crop Growth)
68.	Cq_MycMaxInf[Cr]	Fraction of crop roots infected by mycorrhiza for a soil layer where the Rt_MTInfFrac parameter is 1	dimensionless	0 – 1 (.25)	(Crop Library/ Mycorrhiza Fraction)
69.	Cq_NFixDayFrac[Cr]	Fraction of current N deficit derived from atmospheric N_2 fixation per day for each crop type, if Cq_NFixVariable = 0 ('false').	day^{-1}	0 – 1 (0)	(Crop Library/N Fixation)
70.	Cq_NFixDWMaxFrac[Cr]	Maximum fraction of the C_GroRes[Dw] pool that can be respired for N_2 fixation if Cq_NFixVariable = 0 ('false')	day^{-1}	0 – 0.5 (.1)	(Crop Library/N Fixation)

No.	Acronym	Definition	Dimensions	Range of value (Default value)	Input Section (Link location in Excel)
71.	Cq_NFixDWUnitCost[Cr]	Dry weight cost for respiration per unit N_2 fixation, if Cq_NFixVariable = 0 (‘false’)	kg [dw] g^{-1} [N]	0 – 1 (.01)	(Crop Library/N Fixation)
72.	Cq_NFixResp[Cr]	Responsiveness of N_2 fixation to N stress (N in biomass divided by N target), if Cq_NFixVariable = 0 (‘false’)	dimensionless	0 – 5 (1)	(Crop Library/N Fixation)
73.	Cq_NFixVariable?[Cr]	Switch (0 = false, 1 = true) to choose between variable (N-stress dependent) versus constant N_2 fixation as fraction of N deficit	dimensionless	0 or 1 (0)	(Crop Library/N Fixation)
74.	Cq_NutMobC[Cr,SiNut]	Relative rate of transfer, per unit root length density (cm cm^{-3}), from the 'immobile' pool of nutrients to the 'mobile' or sorbed pool, due to Crop root activity	m^2 day^{-1}	0 – 0.02 (0)	Crop Library/Crop effect on nutrient mobility
75.	Cq_PotSuctAlphMax[Cr]	Plant potential where transpiration is (1-Alpha)*potential transpiration,Alpha is a small value (e.g. 0.01). Value could be different depend on crop type.	cm	-6000 – -4000 (-5000)	(Crop Library/Water Uptake)
76.	Cq_PotSuctAlphMin[Cr]	Plant potential where transpiration is Alpha*potential transpiration, Alpha is a small value (e.g. 0.01). Value could be different depend on crop type.	cm	-16000 – -14000 (-15000)	(Crop Library/Water Uptake)
77.	Cq_RainWStorCap[Cr]	Rainfall water stored as thin film at leaf surface	mm	0 – 2 (1)	(Crop Library/Rain Interception)
78.	Cq_RelLightMaxGr[Cr]	Relative light intensity at which shading starts to affect tree growth	dimensionless	0 – 1 (1)	(Crop Library/Light Capture)
79.	Cq_RhizEffKaPC[Cr]	Proportional reduction of the apparent adsorption constant for P due to root activity of the crop, expressed as fraction of N_KaPdef per unit crop root length density	m^2 day^{-1}	0 – 0.2 (0)	(Crop Library/Crop effect on nutrient mobility)
80.	Cq_RtAlloc[Cr]	Fraction of crop growth reserves allocated to root biomass in the absence of water or nutrient stress as a function of crop stage (only for Rt_ACType=2).	day^{-1}	(see Cq_RtAlloc table)	(Crop Library)
81.	Cq_RtAllocResp[Cr]	Crop root allocation responsiveness to water or nutrient (the factor currently in minimum supply) stress; 0 = constant root allocation, 1 = linear response to water and nitrogen stress, >1 more-than-proportional response (only for Rt_ACType = 2)	dimensionless	0 – 2 (2)	(Crop Library/Roots)
82.	Cq_RtDiam[Cr]	Crop root diameter. It is used in calculating water and nutrient uptake.	cm	0.05 – 1 (.02)	(Crop Library/Roots)
83.	Cq_SingleCycle?[Cr]	A parameter deciding what happens after fruits are ripe: 1 = annual that dies back, 0 = perennial that returns to crop stage =1.	dimensionless	0 or 1 (1)	(Crop Library/Annual or Perennial?)

No.	Acronym	Definition	Dimensions	Range of value (Default value)	Input Section (Link location in Excel)
84.	Cq_SLA[Cr]	Crop specific leaf area = green surface area (one-sided) per unit leaf dry weight, for each crop species as a function of crop growth stage. For Cq_Atype =1, .., 5, default values are provided. Cq_AType = 6, .,10 user defined, as before.	$m^2\ g^{-1}$	(see Cq_SLA table)	(Crop Library)
85.	Cq_TimeGen[Cr]	Length of generative stage for each crop. For Cq_Atype =1, .., 5, default values are provided, but can be modified to adopt the default crop parameters to local conditions.	days	0 – 1000 (30)	(Crop Library/Crop Stage)
86.	Cq_TimeVeg[Cr]	Length of vegetative stage for each crop. For Cq_Atype =1, .., 5, default values are provided, but can be modified to adopt the default crop parameters to local conditions.	days	0 – 1000 (60)	(Crop Library/Crop Stage)
87.	Cq_TranspRatio[Cr]	Amount of water needed per unit dry matter production of each crop species. For Cq_Atype =1, .., 5, default values are provided. For Cq_AType=6, .., 10 user defined	$l\ kg^{-1}$	200 – 600 (300)	(Crop Library/Crop Growth)
88.	Cq_WeedType	Weed type. This is user defined. Weed biomass growth follows the rules of crop growth. It takes the same type of parameters as crop. All the related input parameters are in Excel sheet	dimensionless	(5)	Management/Weed Growth
89.	CW_EnergyDrivenEpot?	Switch (1 = yes, 0 = no) to determine whether the crop water demand driven by Epot	dimensionless	(1)	Soil Evaporation
90.	E_BulkDens	Bulk density used in converting soil mass movement to changes in volume of topsoil per zone	$g\ cm^{-3}$	0.5 – 1.6 (1.4)	(Soil Hydraulic)
91.	E_CovEffT[Tree]	Tree cover efficiency factor (per unit tree LAI)	dimensionless	0 – 1 (.5)	(Tree Library/Erosion Protection)
92.	E_EntrailmentCoeffBare-Plot	Entrailment coefficient for sediment movement (Rose equation) in the absence of vegetative soil cover	Ton (soil) $mm^{-1}\ m^2$	0 – 1 (.002)	Soil Erosion and Sedimentation
93.	E_ErosiType	Parameter to decide on model of erosion used. 1 = using USLE, 0 = using Rose Equation	dimensionless	0 or 1 (0)	Soil Erosion and Sedimentation
94.	E_IntvPloughPlant	Length of ploughing time	julian days	1 – 365 (10)	Management/Tillage
95.	E_PloughBefPlant?	Paramater governing option to plough before planting (0 = no ploughing, 1 = ploughing before planting)	dimensionless	0 or 1 (0)	Management/Tillage
96.	E_PloughDoY	Date of ploughing	julian days	1 – 365 (364)	Management/Tillage
97.	E_PloughY	Year of ploughing	dimensionless	0 – 100 (100)	Management/Tillage
98.	E_RainFac	A multiplier determining impact of rainfall on soil erosion, for calculation soil loss using USLE	dimensionless	0 – 10 (1)	Soil Erosion and Sedimentation

No.	Acronym	Definition	Dimensions	Range of value (Default value)	Input Section (Link location in Excel)
99.	E_SoilMoveperPlough	Amount of soil moved per ploughing event, for calculation soil loss using USLE	kg m^{-2}	0 – 500 (399)	Soil Erosion and Sedimentation
101.	E_SoilType	Type of soil. 1 = medium, 2 = sandy, 3 = clay	dimensionless	1, 2, 3 (1)	Soil Erosion and Sedimentation
101.	E_TillZone?[Zone]	On/off switch for tilling activity in each zone (0 = no tillage, 1 = with tillage)	dimensionless	0 or 1 (0, 1, 1, 1)	Management/Tillage
102.	Evap_InitSlashM	Initial moisture content of slashed vegetation	fraction	(0.4)	Soil Evaporation
103.	Evap_InitWoodM	Initial moisture content of slashed wood	fraction	(0.25)	Soil Evaporation
104.	Evap_MulchEffSurfLit	Effect of mulch on the amount of water evaporating from the soil	dimensionless	1	Soil Evaporation
105.	Evap_SlashDryFact	Factor determined of water of slashed vegetation will evaporated	fraction	0 – 1 (0.5)	Soil Evaporation
106.	Evap_TransRedFractionBy-Can InterceptedWater	The evaporation of water intercepted by plant canopies will reduce the potental transpiration by satisfying part of the energy-driven potential evapotranspiration; this parameter determines the fraction of canopy interception transpiration that will be reduce from Epot before we determine plant demand. Lower values would reflect: 1) rainfall at night (evaporation not during peak of transpiration) 2) more open landscapes where more dry wind comes in from outside the plot.		(0.5)	Soil Evaporation
107.	Evap_WoodDryFact	Factor determined of water of slashed wood will evaporated	fraction	0 – 1 (0.25)	Soil Evaporation
108.	GHG_LitMinMultiplier	Multiplier of litter mineralization for quick modifications of nitrogen oxide emission	dimensionless	(1)	Soil Water & Nutrient/ Nox emissions
109.	GHG_N_2_per_NOx	Ratio of nitrous and nitric oxide	dimensionless	See graph GHG_N_2perNOx	Soil Water & Nutrient/ Nox emissions
110.	LF_FracGWReleaseAsInflow	The fraction of groundwater that flow out that reaches the simulated zone (this depends on subsoil stratification and landscape characteristics beyond the scope of out current model)	dimensionless	(0)	Agroforestry Zone
111.	LF_GWReleaseFraction	The fraction of the current stock of groundwater that flows out on a daily basis. A stock of groundwater stored uphill depends on the 'number of plots uphill'.	dimensionless	(.05)	Agroforestry Zone

No.	Acronym	Definition	Dimensions	Range of value (Default value)	Input Section (Link location in Excel)
112.	LF_SubSurfInflow4	Amount of sub surface water inflow in layer 4	mm day^{-1}	0 – 5 (0)	Agroforestry zone
113.	Mc_Carbon	Proportion of total carbon in plant litter and residue	dimensionless	0 – 0.5 (.42)	Soil Organic Matter and Litter Quality/Litter Quality
114.	Mc_CExtOrg[type]	Carbon concentration of external input	dimensionless	0 – 1 (.4)	Litter Quality/Quality of Ext. Organic Input
115.	Mc_CNRatInitMetab[zone]	Initial C:N ratio metabolic pool of litter	dimensionless	(8)	Soil Organic Matter and Litter Quality/Initial C & N in Litter Pool
116.	Mc_LignExtOrg[Type]	Lignin concentration of external input.	dimensionless	0 – 1 (.2)	Soil Organic Matter and Litter Quality/Quality of Ext. Organic Input
117.	Mc_PolypExtOrg[Type]	Polyphenol concentration of external input	dimensionless	0 – 1 (0)	Soil Organic Matter and Litter Quality/Quality of Ext. Organic Input
118.	Mc_RelKActLit	Decomposition rate of active surface litter pool relative to decomposition rate of active soil fraction pool. It's assumed the decomposition rate of active surface litter and active soil fraction is the same.	dimensionless	(.8)	Soil Organic Matter and Litter Quality/ Other Factors Affecting Decomposition
119.	Mc_RelKMetabLit	Decomposition rate of metabolic surface litter pool relative to decomposition rate of metabolic soil litter pool. It's adopted from century model, the decomposition rate of metabolic surface litter pool = 0.028 per week = 0.04 per day and the decomposition rate of metabolic soil litter pool = 0.35 per week = 0.05 per day.	dimensionless	(.8)	Soil Organic Matter and Litter Quality/ Other Factors Affecting Decomposition
120.	Mc_RelKPassLit	Decomposition rate of passive surface litter pool relative to decomposition rate of passive soil fraction pool. It's assumed the decomposition rate of passive surface litter and passive soil fraction is the same.	dimensionless	(1)	Soil Organic Matter and Litter Quality/ Other Factors Affecting Decomposition
121.	Mc_RelKSlwLit	Decomposition rate of slow surface litter pool relative to decomposition rate of slow soil fraction pool. It's assumed the decomposition rate of slow surface litter and slow soil fraction is the same.	dimensionless	(1)	Soil Organic Matter and Litter Quality/ Other Factors Affecting Decomposition

No.	Acronym	Definition	Dimensions	Range of value (Default value)	Input Section (Link location in Excel)
122.	Mc_RelKStrucLit	Decomposition rate of structural surface litter pool relative to decomposition rate of structural soil litter pool. It's adopted from century model, the decomposition rate of structural surface litter pool = 0.076 per week = 0.010857 per day and the decomposition rate of structural soil litter pool = 0.094 per week = 0.013429 per day.	dimensionless	(0.808511)	Soil Organic Matter and Litter Quality/ Other Factors Affecting Decomposition
123.	Mc2_Clay	Proportion of clay in soil (only for soil organic matter type 2)	dimensionless	0 – 1 (.316)	Soil Organic Matter and Litter Quality/ Other Factors Affecting Decomposition
124.	Mc2_ClayCoeffCref	Coefficient of clay based on tabulated Cref for soil organic matter type 2	dimensionless	(.94)	Soil Organic Matter and Litter Quality/ Other Factors Affecting Decomposition
125.	Mc2_ CNRatInitMetab[zone]	Initial C:N ratio metabolic pool of soil organic matter	dimensionless	(8)	Soil Organic Matter and Litter Quality/Initial C & N in SOM Pool
126.	Mc2_CorgInitMeth3	Initial soil organic carbon value in soil organic matter pool using Type 3.	gr cm^{-2}	(2)	Soil Organic Matter and Litter Quality/ Initial C & N in SOM Pool
127.	Mc2_CorgpCref	Initial soil organic carbon value in soil organic matter pool using Type 3.	gr cm^{-2}	(.8)	Soil Organic Matter and Litter Quality/ Initial C & N in SOM Pool
128.	Mc2_CrefMeth3	Initial C-ref value in soil organic matter pool using Type 2.	gr cm^{-2}	(3)	Soil Organic Matter and Litter Quality/ Initial C & N in SOM Pool
129.	Mc2_CrefOffset	Constant for C reference tabulated for soil organic matter type 2.	dimensionless	1.256	Soil Organic Matter and Litter Quality/ Other Factors Affecting Decomposition
130.	Mc2_KAct	Decay rate for decomposition of active pool of soil organic matter	dimensionless	(.02)	Soil Organic Matter and Litter Quality/ Other Factors Affecting Decomposition

No.	Acronym	Definition	Dimensions	Range of value (Default value)	Input Section (Link location in Excel)
131.	Mc2_KMetab	Decay rate for decomposition of active pool of soil organic matter	dimensionless	(.05)	Soil Organic Matter and Litter Quality/Other Factors Affecting Decomposition
132.	Mc2_KPass	Decay rate for decomposition of active pool of soil organic matter	dimensionless	(.0000186)	Soil Organic Matter and Litter Quality/Other Factors Affecting Decomposition
133.	Mc2_kRelLayer[SoilLayer]	Factor determined decay rate for decomposition of active, passive and slow pool for each soil layer (relative to decay rate for decomposition for each pool).	fraction	(1, .8, .7, .6)	Soil Organic Matter and Litter Quality/ Other Factors Affecting Decomposition
134.	Mc2_KSlw	Decay rate for decomposition of active pool of soil organic matter	dimensionless	(.000543)	Soil Organic Matter and Litter Quality/Other Factors Affecting Decomposition
135.	Mc2_KStruc	Decay rate for decomposition of active pool of soil organic matter	dimensionless	(.013429)	Soil Organic Matter and Litter Quality/Other Factors affecting Decomposition
136.	Mc2_pH	Soil pH (only for soil organic matter type 2)	dimensionless	(5)	Soil Organic Matter and Litter quality/ Other Factors Affecting Decomposition
137.	Mc2_pHCoeffCref	Coefficient of pH based on tabulated of Cref for soil organic matter type 2	dimensionless	-.156	Soil Organic Matter and Litter Quality/Other Factors Affecting Decomposition
138.	Mc2_RainTransfer[Pool]	Rain factor which control transferring process of litter to SOM pool	dimensionless	.001	Soil Organic Matter and Litter Quality/Litter → SOM Transfer
139.	Mc2_Silt	Proportion of silt in soil (only for soil organic matter type 2)	dimensionless	0 – 1 (.2)	Soil Organic Matter and Litter Quality/Other Factors Affecting Decomposition
140.	Mc2_SiltClayCoeffCref	Coefficient of clay and silt based on tabulated Cref for soil organic matter type 2	dimensionless	(.703219)	Soil Organic Matter and Litter Quality/Other Factors Affecting Decomposition
141.	Mc2_SoilTillTransfer[Pool]	Soil tillage factor which control transferring process of litter to SOM pool	dimensionless	(1)	Soil Organic Matter and Litter Quality/Litter → SOM Transfer

No.	**Acronym**	**Definition**	**Dimensions**	**Range of value (Default value)**	**Input Section (Link location in Excel)**
142.	Mc2_ SOMDistribution[SoilLayer]	Relative distribution of carbon between different soil layers	fraction	0 – 1 (1, .2, .1, .05)	Soil Organic Matter and Litter Quality/SOM Distribution
143.	Mc2_SOMInitType	Parameter defining methods to initialize soil organic matter pool. Three methods are provided for initializing the soil organic matter pools: Type = 1 the user can specify all pool sizes for all zones, Type = 2 the user can specify the size of all pools relative to those for a forest soil (Cref) that is calculated from soil texture data, Type = 3 the user specifies the Corg and Cref directly, but otherwise follows the procedure of Type 2	dimensionless	1, 2, 3 (1)	Soil Organic Matter and Litter Quality/Initial C & N in SOM Pool
144.	Mc2_WormTransfer[Pool]	Worm factor which control transferring process of litter to SOM pool	dimensionless	0.003 – 0.1 (Struc, Metab and Act = .1; Slow = .3; Pass = .003)	Soil Organic Matter and Litter Quality/ Litter → SOM Transfer
145.	Mn_CNAct	C:N ratio of active pools	dimensionless	5 – 10 (8)	Soil Organic Matter and Litter Quality/C:N Ratio of Litter Pool
146.	Mn_CNPass	C:N ratio of passive pools	dimensionless	8 – 15 (11)	Soil Organic Matter and Litter Quality/C:N Ratio of Litter Pool
147.	Mn_CNSlw	C:N ratio of slow pools	dimensionless	8 – 15 (11)	Soil Organic Matter and Litter Quality/C:N Ratio of Litter Pool
148.	Mn_CNStruc	C:N ratio of structural pools	dimensionless	100 – 200 (150)	Soil Organic Matter and Litter Quality/C:N Ratio of Litter Pool
149.	Mn_ExtOrgN[Type,SiNut]	N or P concentration of external input	dimensionless	0 – 0.1 (N = .05, .1; P = .005, .001)	Soil Organic Matter and Litter Quality/Quality of Ext. Organic Input
150.	Mn_FertDissFrac[SiNut]	Daily fraction of fertilizer dissolved	Dimensionless	(N = 0.3, P = 0.5)	Soil Water & Nutrient/Fertilizer Movement

No.	Acronym	Definition	Dimensions	Range of value (Default value)	Input Section (Link location in Excel)
151.	Mn_InitAct[Zone]	Initial amount of N in active Litter pool of each zone	mg cm^{-3}	0 – 1 (.00002)	Soil Organic Matter and Litter Quality/Initial C & N in Litter Pool
152.	Mn_InitMetab[Zone]	Initial amount of N in metabolic Litter pool of each zone	mg cm^{-3}	0 – 1 (0)	Soil Organic Matter and Litter Quality/Initial C & N in Litter Pool
153.	Mn_InitPass[Zone]	Initial amount of N in passive Litter pool of each zone	mg cm^{-3}	0 – 1 (.0001)	Soil Organic Matter and Litter Quality/Initial C & N in Litter Pool
154.	Mn_InitSlw[Zone]	Initial amount of N in slow Litter pool of each zone	mg cm^{-3}	0 – 1 (.000001)	Soil Organic Matter and Litter Quality/Initial C & N in Litter Pool
155.	Mn_InitStruc[Zone]	Initial amount of N in structural Litter pool of each zone	mg cm^{-3}	0 – 1 (0)	Soil Organic Matter and Litter Quality/Initial C & N in Litter Pool
156.	Mn_LatFlowFertKm	Runoff flow that causes half of the (undissolved) surface fertilizer to move to the next zone	mm	(10)	Soil Water & Nutrient/Fertilizer Movement
157.	Mn_NutRatAct[P]	Ratio of N to P (N:P) in active organic matter pools	dimensionless	1 – 10 (10)	Soil Organic Matter and Litter Quality/C:N Ratio of Litter Pool
158.	Mn_NutRatMetab[P]	Ratio of N to P (N:P) in metabolic organic matter pools	dimensionless	1 – 10 (10)	Soil Organic Matter and Litter Quality/C:N Ratio of Litter Pool
159.	Mn_NutRatPass[P]	Ratio of N to P (N:P) in passive organic matter pools	dimensionless	1 – 10 (10)	Soil Organic Matter and Litter Quality/C:N Ratio of Litter Pool
160.	Mn_NutRatSlw[P]	Ratio of N to P (N:P) in slow organic matter pools	dimensionless	1 – 10 (10)	Soil Organic Matter and Litter Quality/C:N Ratio of Litter Pool
161.	Mn_NutRatStruc[P]	Ratio of N to P (N:P) in structural organic matter pools	dimensionless	1 – 10 (10)	Soil Organic Matter and Litter Quality/C:N Ratio of Litter Pool

No.	Acronym	Definition	Dimensions	Range of value (Default value)	Input Section (Link location in Excel)
162.	Mn2_InitAct[Zone]	Initial amount of N in active SOM pool of each zone	mg cm^{-3}	0 – 1 (.2)	Soil Organic Matter and Litter Quality/Initial C & N in SOM Pool
163.	Mn2_InitMetab[Zone]	Initial amount of N in metabolic SOM pool of each zone	mg cm^{-3}	0 – 1 (0)	Soil Organic Matter and Litter Quality/Initial C & N in SOM Pool
164.	Mn2_InitPass[Zone]	Initial amount of N in passive SOM pool of each zone	mg cm^{-3}	0 – 1 (3.9)	Soil Organic Matter and Litter Quality/Initial C & N in SOM Pool
165.	Mn2_InitSlw[Zone]	Initial amount of N in slow SOM pool of each zone	mg cm^{-3}	0 – 1 (1)	Soil Organic Matter and Litter Quality/Initial C & N in SOM Pool
166.	Mn2_InitStruc[Zone]	Initial amount of N in structural SOM pool of each zone	mg cm^{-3}	0 – 1 (0)	Soil Organic Matter and Litter Quality/Initial C & N in SOM Pool
167.	Mn2_PassRelLayer[SoilLayer]	Proportional distribution of passive pool	fraction	(1, 1.2, 1.4, 1.6)	Soil Organic Matter and Litter Quality/Initial C & N in SOM Pool
168.	N_BypassMacroi[Zone]	Prefential flows of nutrients in the leachate relative to average concentration * water flow; values < 1 indicates retardation of nutrients due to bypass flow of water in macropores at soil layer i	dimensionless	0 – 2 (1)	Soil Water and Nutrient/Macropore Bypass Flow
169.	N_DiffCoef[SiNut]	Nitrogen diffusion coefficient	cm^{2} day^{-1}	0 - 1 (N = 1, P = .76896)	Soil Water and Nutrient /Diffusivity coefficient
170.	N_FracNO3i[Zone]	Fraction of NO_3 of total N in *i*-th soil layer	dimensionless	0 - 1 (0.4)	Soil Water and Nutrient/Nitrate Fraction
171.	N_ImInit[Zone,SiNut]	Initial amount of nutrient in immobile pool of each zone	mg cm^{3}	0 – 0.1 (N = .05, P = .01)	Soil Water and Nutrient /Initial Immobile Nutrient
172.	N_KaNH4i[Zone]	Apparent (instantaneous) adsorption constant or ratio of amount NH_4 adsorbed and amount in solution for *i*-th layer	mg cm^{-3}	0 – 1 (5)	Soil Water and Nutrient/Adsorption constant for N

No.	Acronym	Definition	Dimensions	Range of value (Default value)	Input Section (Link location in Excel)
173.	N_KaNO3i[Zone]	Apparent (instantaneous) adsorption constant or ratio of amount NO_3 adsorbed and amount in solution for i-th layer	mg cm^{-3}	0 – 1 (.3)	Soil Water and Nutrient /Adsorption constant for N
174.	N_KaPDefi[Zone]	Apparent (instantaneous) adsorption constant for inorganic P, or ratio of amount of inorganic P adsorbed ant the amount in soil solution; the adsorption constant depends on the P concentration on soil solution and is read in a tabular form (as graphical input parameter).	mg cm^{-3}	(see N_KaPDef*i* table)	(Phosphorus/to P sorption data)
● 175.	N_Lat4InflowRelConc	Nutrient concentrations in the incoming sub-surface flows into zone 4, relative to the current average nutrient concentration in that layer across all zones in the simulated area	dimensionless	0 – 10 (1)	Agroforestry Zone
176.	N_NIniti[Zone,SiNut]	Initial amount of nutrient in soil layer i of each zone	mg cm^3	0 – 0.5 (N layer 1 = .003, layer 2 – 4 = .01 ; P layer 1 = .1, layer 2 = .08, layer 3 – 4 = .04)	For P, (Phosphorus/Initial P availability Index per Zone and Layer) For N, (Nitrogen)
● 177.	N_NutMobi[SiNut]	Relative rate of transfer from the 'immobile' pool of nutrients to the 'mobile' or sorbed pool, due to processes other than root activity in soil layer i	day^{-1}	0 – 0.02 (0)	Soil Nutrient/Nutrient Mobilization
● 178.	N_RtSynloci	Root synlocation, or degree to which roots of the crop and tree are co-occurring within the various soil layers, affecting the way in which benefits of rhizosphere modification are shared; 1 = sharing of rhizosphere modifications by all roots present, based on their share in total root length, 0 = complete monopoly by roots modifying the rhizosphere	dimensionless	0 – 1 (.5)	Roots and Mycorrhiza
● 179.	N_UseNGassLossEst?	A switch determining simulate system with gaseous N losses. 0 = no gaseous N losses, 1 = with gaseous N losses	dimensionless	(0)	Soil Water & Nutrient
● 180.	N15_Addi [Zone]	Initial amount of N^{15} in soil layer i of each zone	mg cm^{-3}	(0)	N^{15} model sector
● 181.	P_BurnLab	Amount of labour involved in burning the field per unit simulated filed	person days ha^{-1}	(see excel sheet Profitability)	(Profitability)
● 182.	P_CfertPrice[SiNut,Price]	Cost of fertilizer at social and private prices, respectively.	currency unit kg^{-1}	(see excel sheet Profitability)	(Profitability)

No.	Acronym	Definition	Dimensions	Range of value (Default value)	Input Section (Link location in Excel)
183.	P_CHarvLab[Cr]	Amount of labour involved in harvesting crop products per unit dry weight	person days Mg^{-1} per cropping season	(see excel sheet Crop Library)	(Crop Library/Profitability)
184.	P_CNuFerAppperCropSeason	Number of fertilizer application per cropping season	dimensionless	Any integer value (2)	Profitability
185.	P_CPestContLab[Cr]	Amount of labour involved in pest control per cropping season	person days ha^{-1} per cropping season	(see excel sheet Crop Library)	(Crop Library/Profitability)
186.	P_CPestContPrice[Price]	Amount of direct costs (outside labour) involved in pest control per cropping season	currency unit per ha^{-1} per cropping season	(see excel sheet Profitability)	(Profitability)
187.	P_CPlantLab[Cr]	Amount of labour involved in planting per cropping season	person days ha^{-1} per cropping season	(see excel sheet Crop Library)	(Crop Library/Profitability)
188.	P_CropProfThreshold	Threshold value for crop profitability. Relevan to parameter P_UseCropStopRule? = 1	Currency unit	(100000)	Management/Ending a Crop Cycle
189.	P_CSeedPrice[Cr,Price]	Cost of crop seed per kg at social and private prices, respectively.	currency unit kg^{-1}	(see excel sheet Crop Library)	(Crop Library/Profitability)
190.	P_CWeedLab[Cr]	Amount of labour involved in weeding per cropping season	person days ha^{-1} per cropping season	(see excel sheet Crop Library)	(Crop Library/Profitability)
191.	P_CyieldPrice[Cr, Price]	Price of crop yield per unit dry weight at social and private prices, respectively.	currency unit kg^{-1}	(see excel sheet Crop Library)	(Crop Library/Profitability)
192.	P_DiscountRate	Discount rate (% per year) that applies to both social and private prices	% $year^{-1}$	(see excel sheet Profitability)	(Profitability)
193.	P_ExtOrgPrice [Type,Price]	Price of external organic input	currency unit kg^{-1}	(see excel sheet Profitability)	(Profitability)
194.	P_FenceMatCost[Price]	Price of off-farm material used for building or maintaining a fence around the field	currency unit ha^{-1}	(see excel sheet Profitability)	(Profitability)
195.	P_LabourforPestContrl ?	A switch 0 0r 1 for pesticide application related to the use of labour (1 = pesticide application, 0 = no pesticide application)	dimensionless	0 or 1	Profitability
196.	P_LabourforWeed ?	A switch 0 0r 1 for weeding application related to the use of labour (1 = weeding application, 0 = no weeding application)	dimensionless	0 or 1	Profitability

No.	Acronym	Definition	Dimensions	Range of value (Default value)	Input Section (Link location in Excel)
197.	P_TFruitHarvLab	Amount of labour involved in harvesting fruits per unit dry weight	person days kg^{-1}	(see excel sheet Tree Library)	(Tree Library/Profitability)
198.	P_TFruitPrice[Price]	Price of tree fruit yield per unit dry weight at social and private prices, respectively.	currency unit kg^{-1}	(see excel sheet Tree Library)	(Tree Library/Profitability)
199.	P_TLatexHarvLab	Amount of labour involved in harvesting latex per unit dry weight	person days kg^{-1}	(see excel sheet Tree Library)	(Tree Library/Profitability)
200.	P_TLatexPrice[Price]	Price of tree latex yield per unit dry weight at social and private prices, respectively.	currency unit kg^{-1}	(see excel sheet Tree Library)	(Tree Library/Profitability)
201.	P_TNuFerApp[Tree]	Number of fertilizer application per year	dimensionless	Any integr value (2)	Profitability
202.	P_TPlantLab	Amount of labour involved in planting trees per unit dry weight	person days kg^{-1}	(see excel sheet Tree Library)	(Tree Library/Profitability)
203.	P_TPrunLab[Tree]	Amount of labour involved in pruning trees per unit dry weight	person days kg^{-1}	(see excel sheet Tree Library)	(Tree Library/Profitability)
204.	P_TPrunPrice[Price]	Price of tree prunings harvested from the field per unit dry weight at social and private prices, respectively.	currency unit kg^{-1}	(see excel sheet Tree Library)	(Tree Library/Profitability)
205.	P_TSeedPrice[Price]	Costs of tree planting material per unit initial tree biomass at social and private prices, respectively.	currency unit $tree^{-1}$	(see excel sheet Tree Library)	(Tree Library/Profitability)
206.	P_TWoodHarvLab	Amount of labour involved in harvesting wood products per unit dry weight	person days kg=1	(see excel sheet Tree Library)	(Tree Library/Profitability)
207.	P_TWoodPrice[Price]	Price of tree wood product yield per unit dry weight at social and private prices, respectively.	currency unit kg^{-1}	(see excel sheet Tree Library)	(Tree Library/Profitability)
208.	P_UnitLabCost[Price]	Cost per unit labour at social and private prices, respectively	currency unit person $days^{-1}$	(see excel sheet Profitability)	(Profitability)
209.	P_UseCropStopRule?	A switch determining the simulation will continue to growth crop or not when the previous crop profitability lower than the threshold value. 0 means continue to growth crop, 1 = stop to growth crop	dimensionless	(0)	Management/Ending a Crop Cycle
210.	PD_CeatenBy[Cr,Animals]	Fraction of crop component lost if eaten by animals. Default animals are pigs, monkey, locust, nematode, goat, buffalo and birds	dimensionless	0 – 1 (0)	(Crop Library/Sensitivity to Pest Damage)

No.	Acronym	Definition	Dimensions	Range of value (Default value)	Input Section (Link location in Excel)
211.	PD_CFrugivore?[Animals]	A switch determining the presence of attack by each default animal. 0 = animals is not a crop frugivore,1 = animal is frugivore	dimensionless	0 or 1 (0)	Pest and Disease
212.	PD_CFrugivory[Cr]	Constant daily fraction of crop fruit biomass removed due to the action of frugivores	dimensionless	0 – 1 (0)	Pest and Diseases
213.	PD_CHerbivore?[Animals]	A switch determining the presence of attack by each default animal. 0 = animals is not a crop herbivore,1 = animal is herbivore	dimensionless	0 or 1 (0)	Pest and Disease
214.	PD_CHerbivory[Cr]	Constant daily fraction of crop leaf biomass removed due to the action of herbivores	dimensionless	0 – 1 (0)	Pest and Diseases
215.	PD_CRhizovore?[Animals]	A switch determining the presence of attack by each default animal. 0 = animals is not a crop rhizovore,1 = animal is rhizovore	dimensionless	0 or 1 (0)	Pest and Disease
216.	PD_CRhizovory[Cr]	Constant daily fraction of crop root biomass removed due to the action of rhizovores	dimensionless	0 – 1 (0)	Pest and Diseases
217.	PD_FenceBuildDOY	Schedule for day of fencing for each fencing event. A graphical input.	julian days	(see PD_Fence-BuildDOY graph)	Pest and Disease
218.	PD_FenceBuildLab	Amount of labour needed to build fence for each fencing event. A graphical input.	person days	(see PD_Fence-BuildLab graph)	Pest and Disease
219.	PD_FenceBuildY	Schedule for year of fencing for each fencing event A graphical input.	dimensionless	(see PD_Fence-BuildY graph)	Pest and Disease
220.	PD_FenceDecK	Daily fractional decay of fence quality	day^{-1}	0 – 1 (.02)	Pest and Diseases
221.	PD_FenceFullQua	Maximum quality of fence	dimensionless	1 – 4 (2)	Pest and Diseases
222.	PD_FenceMaint?	Switch determining fence maintenance. 1 = fence maintenance will be done automatically, 0 = no fence maintenance	dimensionless	0 or 1 (0)	Pest and Disease
223.	PD_FenceMUnit	Unit improvement of fence quality once it falls below the threshold set in PD_FenceQThresh	dimensionless	0 – 2 (.25)	Pest and Disease
224.	PD_FenceQThresh	Threshold of (relative) fence quality below which labour will be used to repair the fence	dimensionless	0 – 2 (1.1)	Pests and Disease
225.	PD_HalfFenceTime	Time constant of decay of fence quality: time interval after which quality is reduced by 50%	days	0 – 365 (50)	Pest and Disease

No.	Acronym	Definition	Dimensions	Range of value (Default value)	Input Section (Link location in Excel)
226.	PD_ JumptheFence?[animals]	The degree to which animals are deterred by a fence from entering the plot	-	0 – 1 (0)	Pest and Diseases
227.	PD_ PopDensOutside[animals]	Population density outside the plot, influencing the presence	-	0 or 1	Pest and Diseases
228.	PD_TEatenBy?[Animals]	A switch determining tree attacks by specific animals. Default animals are pigs, monkey, locust, nematode, goat, buffalo and birds. 0 = no attack, 1 = attacked	0 or 1 (0)	0 – 1 (0)	(Tree parameters/Pest Impacts)
229.	PD_TFrugivore?[Animals]	A switch determining the presence of attack by each default animal. 0 = animals is not a tree frugivore,1 = animal is frugivore	dimensionless	0 or 1 (0)	Pest and Disease
230.	PD_Tfrugivory&Abort[Tree]	Constant daily fraction of tree fruit biomass removed due to the action of frugivores	-	0 – 1 (0)	Pest and Diseases
231.	PD_THerbivore?[Animals]	A switch determining the presence of attack by each default animal. 0 = animals is not a tree herbivore,1 = animal is herbivore	dimensionless	0 or 1 (0)	Pest and Disease
232.	PD_THerbivory[Tree]	Constant daily fraction of tree leaf biomass removed due to the action of herbivores	-	0 – 1 (0)	Pest and Diseases
233.	PD_TLignivory[Tree]	Constant daily fraction of tree woody stem biomass removed due to the action of lignivores	-	0 – 1 (0)	Pest and Diseases
234.	PD_TLignovore?[Animals]	A switch determining the presence of attack by each default animal. 0 = animals is not a tree lignovore,1 = animal is lignovore	dimensionless	0 or 1 (0)	Pest and Disease
235.	PD_TRhizovore?[Animals]	A switch determining the presence of attack by each default animal. 0 = animals is not a tree rhizovore,1 = animal is rhizovore	dimensionless	0 or 1 (0)	Pest and Disease
236.	PD_TRhizovory[Tree]	Constant daily fraction of tree root biomass removed due to the action of rhizovores	-	0 – 1 (0)	Pest and Diseases
237.	Rain_AType	A number 1, 2 or 3 to decide rainfall rate (1= rainfall rate follows precipitation data from external file, rainfall rate follows tabulated data, 2 = rainfall rate follows random generator, 3= rainfall rate follows tabulated monthly total data)	dimensionless	1, 2 or 3 (1)	Rainfall
238.	Rain_BoundHeaLi	Boundary value between heavy and light rain (only for Rain_AType=1)	mm	20 – 30 (25)	Rainfall
239.	Rain_CoeffVar2	Coefficient variation of rainfall in mm, used in rainfall generated randomly (Rain_Atype=2)	dimensionless	0 – 1 (.05)	Rainfall
240.	Rain_CoeffVar3	Coefficient variation of rainfall in mm, rainfall based on tabulated monthly rainfall (Rain_Atype=3)	dimensionless	0 – 1 (.05)	Rainfall

No.	Acronym	Definition	Dimensions	Range of value (Default value)	Input Section (Link location in Excel)
241.	Rain_Cycle?	Parameter governing ways to read rainfall data. Corresponds to Rain_AType=1 (0 = use multiple year rainfall data, 1 = use 1 year data in cycle/continuously)	dimensionless	0 or 1 (1)	Rainfall
242.	Rain_Data	Actual daily rainfall data. Entered as graphical function or read from Wanulcas.xls (Stella non-CRT users only). Corresponds to Rain_AType=1.	mm	(see table in excel sheet weather)	(WEATHER)
243.	Rain_DayP	Probability of raining each day as a function of Julian day scaled monthly. Corresponds to Rain_AType=2 and 3.	dimensionless	0 – 1 (.32)	Rainfall
244.	Rain_GenSeed	Seed Random Generator. For Rain_AType=2 and 3.	dimensionless	1 – 32767 (300)	Rainfall
245.	Rain_Heavy	Average precipitation rate of on a heavy rain day; for Rain_AType=2.	mm day^{-1}	0 – 100 (42)	Rainfall
246.	Rain_HeavyP	Probability of heavy rain; for Rain_AType=2.	dimensionless	0 – 1 (.5)	Rainfall
247.	Rain_IntensCoefVar	Coeficient variance of rain intensity. Rain intensity is a factor affecting water infiltration. It is assumes to follow normal distribution with an average of Rain_IntensMean and standard deviation Rain_IntensMean*Rain_IntensCoefVar.	dimensionless	(.3)	Rainfall
248.	Rain_IntensMean	Average rain intensity per hour. Rain intensity is a factor affecting water infiltration. It is assumes to follow normal distribution with an average of Rain_IntensMean and standard deviation Rain_IntensMean*Rain_IntensCoefVar	mm hr^{-1}	(50)	Rainfall
249.	Rain_IntercDripRt	The rate of water dripping from water on interception surface	mm hr^{-1}	(10)	Rainfall
250.	Rain_IntMult	Indicates the maximum temporary storage of water on interception surfaces	dimensionless	(3)	Rainfall
251.	Rain_Light	Average precipitation rate of a light rain day day; for Rain_AType=2.	mm day^{-1}	0 – 40 (9)	Rainfall
252.	Rain_MaxIntDripDur	Maximum value of water interception delay before start to dripping	mm hr^{-1}	(.5)	Rainfall
253.	Rain_MonthTot	Tabulated data of monthly rainfall; for Rain_AType=3. Entered as graphical function or read from Wanulcas.xls (Stella non-CRT users only).	mm month^{-1}	(see Rain_MonthTot graph)	Rainfall
254.	Rain_Multiplier	Multiplier of rainfall for quick modifications of rainfall amount	dimensionless	0 – 4 (1)	RUN & OUTPUT SECTION

No.	Acronym	Definition	Dimensions	Range of value (Default value)	Input Section (Link location in Excel)
255.	Rain_PondFlwRt	The rate at which water ponding on the surface will actually flow to a neighbouring zone or plot	mm hr^{-1} per m of zone width	(10)	Rainfall
256.	Rain_PondStoreCp	The storage capacity of water ponding on the surface	mm	(5)	Rainfall
257.	Rain_Weight[Zone]	Input weight value to decide amount of rain falling on each zone relative to other zones (eg. equal rainfall in each zone on area basis means 1:1:1:1)	dimensionless	0 – 10 (1)	Rainfall
258.	Rain_YearStart	Initial year based on rainfall data at which simulation starts	dimensionless	any integer value (0)	Rainfall
259.	Rain_UniorBimodal?	An option to have one or two season of rainfall	dimensionless	2	Rainfall
260.	Rain_Probabiity	Ratio between season 1 and season 2	dimensionless	0.5	Rainfall
261.	Rain_OffSetValue	Influence value of dry month. High value indicates low amount of rainfall at dry season.	dimensionless	-0.5	Rainfall
262.	Rain_ShapeMax	Maximum value of shape. Shape is a basic pattern of rainfall simulator model that use SINUS as the distribution function. This value will be used to determine Pattern value.	dimensionless	1.5	Rainfall
263.	Rain_ShapeMin	Minimum value of shape.	dimensionless	-0.5	Rainfall
264.	Rain_Pattern1Max	Maximum value of pattern. Pattern is calculated from shape value which is the maximum and the minimum value have been adjusted to the maximum and minimum value of total monthly rainfall.	dimensionless	0.06	Rainfall
265.	Rain_Pattern1Min	Minimum value of pattern.	dimensionless	-0.01	Rainfall
266.	Rain_WettestMonthSeason1	The wettest month of the first season (January – June)	dimensionless	1	Rainfall
267.	Rain_WettestMonthSeason2	The wettest month of the second season (July – December)	dimensionless	7	Rainfall
268.	Rain_PeakinessSeason1	The sharpness of the first peak. High value indicates sharper peak.	dimensionless	1	Rainfall
269.	Rain_PeakinessSeason2	The sharpness of the second peak. High value indicates sharper peak.	dimensionless	12	Rainfall
270.	Rain_WeibullParam	Parameter of Weibull distribution. This Weibull parameter is used to predict the value of daily cumulative frequency of rainfall data.	dimensionless	0.93	Rainfall

No.	Acronym	Definition	Dimensions	Range of value (Default value)	Input Section (Link location in Excel)
271.	Rain_MonthlyMeanRainfallMax	Maximum value of monthly mean rainfall	mm	333	Rainfall
272.	Rain_MonthlyMeanRainfallMin	Minimum value of monthly mean rainfall	mm	102	Rainfall
273.	Rain_NumberWetDaypM[Month]	The number of wet day for each month	day	See graph	Rainfall
274.	Rain_MonthlyMeanTotalrainfall [Month]	Monthly mean rainfall on the wet day	mm	See graph	Rainfall
275.	Rain_RelWetPersistencepM [Month]	Monthly relative wet persistence	dimensionless	See graph	Rainfall
276.	Rt_ACType	Parameter governing type of root density data for crop. 0=Lrv data available, 1=Lrv calculated using exponential function model where length root area is constant, 2= Lrv calculated using exponential function model where length root area is derived from root biomass	dimensionless	0, 1, or 2 (0)	Roots and Mycorrhiza/ Crop Root
277.	Rt_ATType	Parameter governing type of root density data for tree. 0=Lrv data available, 1=Lrv is constant calculated using ellipticall function model, 2= Lrv is calculated using elliptical function but dynamically changes according to water or N stress	dimensionless	0, 1 or 2 (0)	Roots and Mycorrhiza/ Tree Root
278.	Rt_CDecDepth[Cr]	Parameter governing decrease of crop root with depth; corresponds to Rt_ACType=1 and Cq_AType.	m^{-1}	0 - 10 (7)	(Crop Library/Roots)
279.	Rt_CDistResp[Cr]	Responsiveness of crop root distribution to the depth at which uptake of the currently limiting resource (water, N or P) is most successful. Value 0 = no response to stress, 0 – 1 = mild response, 1 = proportional change to inverse of relative depth of uptake, > 1 = strong response. Only for Rt_ACType = 2.	dimensionless	0 – 3 (1)	(Crop Library/Roots)
280.	Rt_CHalfLife[Cr]	Crop root half-life (only for Rt_ACType=2)	days	30 – 100 (50)	(Crop Library/Roots)
281.	Rt_CLraConst[Cr]	Total root length per unit area. It is used to calculate crop root density in exponential decrease model (Rt_ACType=1). Also corresponds to Cq_AType.	cm cm^{-2}	0 – 150 (100)	(Crop Library/Roots)
282.	Rt_CLrvmi[Cr]	Maximum crop root length density in i-th soil layer; corresponds to Rt_ACType=0 and Cq_A Type.	cm cm^{-3}	0 – 15 (layer 1 = 5, layer 2 = 3, layer 3 = .3, layer 4 = 0)	(Crop Library/Roots)

No.	Acronym	Definition	Dimensions	Range of value (Default value)	Input Section (Link location in Excel)
283.	Rt_CMultiplier	Multiplier of root for quick modifications of crop root length density	dimensioless	(1)	Root and Mycorrhiza
284.	Rt_CSRL[Cr]	Specific root length (length per unit dry weight) of crop roots	m g^{-1}	50 – 100(200)	(Crop Library/Roots)
285.	Rt_MCHypDiam	Diameter of crop mycorrhizal hyphae	cm	0.001 – 0.05 (.01)	Roots & Mycorrhiza/ Mycorrhiza
286.	Rt_MCHypL	Length of crop mycorrhizal hyphae per unit infected root length	dimensionless	10 – 100 (100)	Roots & Mycorrhiza/ Mycorrhiza
287.	Rt_MCInfFraci	Fraction of crop roots that is mycorrhizal (infected) in i-th soil layer	dimensionless	0 – 1 (layer 1 =.05, layer 2 =.25, layer 3 = .05, layer 4 = 0)	Roots & Mycorrhiza/ Mycorrhiza
288.	Rt_MTHypDiam	Diameter of tree mycorrhizal hyphae	cm	0.001 – 0.05 (.01)	Roots & Mycorrhiza/ Mycorrhiza
289.	Rt_MTHypL	Length of tree mycorrhizal hyphae per unit infected root length	dimensionless	10 – 100 (100)	Roots & Mycorrhiza/ Mycorrhiza
290.	Rt_MTInfFraci[Zone]	Fraction of tree roots that is mycorrhizaal (infected)	dimensionless	0 – 1 (0)	Roots & Mycorrhiza/ Mycorrhiza
291.	Rt_TAlloc[Tree]	Fraction of tree growth reserves allocated to roots in the absence of water or nutrient stress (only for Rt_ATType=2)	dimensionless	0 – 1 (.1)	(Tree Library/Roots)
292.	Rt_TAllocResp[Tree]	Responsiveness of tree root allocation to stress factors; 0 = constant root allocation, 1 = linear response to water and nitrogen stress, >1 more-than-proportional response (only for Rt_ACType = 2),	dimensionless	0 – 2 (2)	(Tree Library/Roots)
293.	Rt_TDecDepthC[Tree]	Parameter governing decrease of tree root with depth ; for Rt_ATType=1	m^{-1}	0 – 10 (3)	(Tree Library/Roots)
294.	Rt_TDistResp[Tree]	Responsiveness of crop root distribution to the depth at which uptake of the currently limiting resource (water, N or P) is most successful. Value 0 = no response to stress, 0 – 1 = mild response, 1 = proportional change to inverse of relative depth of uptake, > 1 = strong response. Only for Rt_ACType = 2.	dimensionless	0 – 5 (2)	(Tree Library/Roots)
295.	Rt_TDistShapeC[Tree]	Tree root distribution shape for Rt_ATType=1 and 2; for a value of 1 root length density decreases as much with horizontal as with vertical distance to the tree stem	dimensionless	0 – 2 (.05)	(Tree Library/Roots)

No.	Acronym	Definition	Dimensions	Range of value (Default value)	Input Section (Link location in Excel)
296.	Rt_THalfLife[Tree]	Tree root half life (only for Rt_ATType=2)	days	30 – 150 (60)	(Tree Library/Roots)
297.	Rt_THostEffForT1[Tree]	An option for simulation root parasitism tree 1 on others tree root	dimensionless	(0)	Root Parasitism
298.	Rt_TLengDiam1[Tree]	Length of (branch) roots of a tree root with a proximal (at stem base) diameter of 1 cm; Intercept (a) of allometric equation (RootLength = a StemDiameterb). Calculation from Functional Branch Analysis (FBA). Input needed to run FBA refer to tree parameterization	cm cm-b	0.01 – 1 (10)	(Tree Library/Roots)
299.	Rt_TLengDiamSlope[Tree]	Power coefficient (b) of allometric equation (RootLength = a StemDiameterb). Calculation from Functional Branch Analysis (FBA). Input needed to run FBA refer to tree parameterization	dimensionless	1 – 3 (1.5)	(Tree Library/Roots)
300.	Rt_TLraX0[Tree]	Total root length per unit area at X(distance to tree)=0 (tree stem). for Rt_ATType=1	cm cm^{-2}	0 – 150 (1)	(Tree Library/Roots)
301.	Rt_TLrvDatai[Zone,Tree]	Tree root density in soil layer .i in each zone; for Rt_ATType=0	cm cm^{-2}	0 – 15 (see excel sheet Tree Library/Roots)	(Tree Library/Roots)
302.	Rt_TMultiplier	Multiplier of root for quick modifications of tree root length density	dimensionless	(1)	Root and Mycorrhiza
303.	Rt_TProxGini	Distribution coefficient of proximal root diameters (CumFreq = (Diam/Diammax)TProxGini of a tree, used in calculation of the specific root length of a tree root system	dimensionless	0.001 – 10 (.3)	(Tree Library/Roots)
304.	Rt_TWghtDiam1[Tree]	Biomass of a (branched) tree root with a proximal (at stem base) diameter of 1 cm; Intercept (a) of allometric equation (Root weight = a StemDiameterb). Calculation from Functional Branch Analysis (FBA). Input needed to run FBA refer to tree parameterization	kg $cm^{-b\ z}$	0.01 – 1 (.5)	(Tree Library/Roots)
305.	Rt_TWghtDiamSlope[Tree]	Power coefficient (b) of allometric equation (RootWeight = a StemDiameterb). Calculation from Functional Branch Analysis (FBA). Input needed to run FBA refer to tree parameterization	dimensionless	1 – 3 (2.3)	(Tree Library/Roots)
306.	S&B_2ndFireafterPileup	Number of days between puile up and secondary burn event	days	1 – 100 (5)	Management/Slash and Burn
307.	S&B_CritMoist	Limit value for internal + adhering (intercepted from rainfall) moisture content of slashed necromass; below this value necromass is categorized as dry and fire can take place	l kg^{-1}	0 – 1(.05)	Management/Slash and Burn

No.	Acronym	Definition	Dimensions	Range of value (Default value)	Input Section (Link location in Excel)
308.	S&B_DailyDeadWoodLitTransf	Rate of transfer of daily dead wood litter per day	fraction day^{-1}	(0.005)	Slash and Burn
309.	S&B_DailyNecromLitTransf	Rate of transfer of necromass litter per day	fraction day^{-1}	(0.01)	Slash and Burn
310.	S&B_DeadWoodFuelFact	Temperature of the fire per unit dry weight of fuel in dead wood	°C kg^{-1}	0 – 100 (.1)	Management/Slash and Burn
311.	S&B_FirImpPSorption	Fire impacts on P sorption, as a function of soil surface temperature increase	dimensionless	(see table in excel sheet Slash&Burn)	Management/Slash and Burn
312.	S&B_FirIndPMobiliz	Fire impact on mobilization fraction of P from the inorganic P immobile pool, as a function of soil surface temperature increase	dimensionless	(see table in excel sheet Slash&Burn)	Management/Slash and Burn
313.	S&B_FirMortSeedBank	Fractional mortality in the weed seed bank as a function of soil surface temperature increment	dimensionless	(see table in excel sheet Slash&Burn)	Management/Slash and Burn
314.	S&B_FuelLoadFactor	Temperature of the fire per unit dry weight of fuel in slashed necromass and structural surface litter	°C kg^{-1}	0 – 100 (10)	Management/Slash and Burn
315.	S&B_MaxDryingPer	The latest time after slashing when fire can occur; if the fuel does not get dry enough before this time, no fire will be occur	days	1 – 200 (30)	Management/Slash and Burn
316.	S&B_MinDryingPer	The earliest time after slashing that fire can occur	days	0 – 100 (20)	Management/Slash and Burn
317.	S&B_NecroBurnFrac	Fraction of surface necromass burnt as a function of fire temperature at the soil surface.	dimensionless	(see table in excel sheet Slash&Burn)	Management/Slash and Burn
318.	S&B_NutVolatFracN	Volatilization fraction of N in the burnt necromass, as a function of soil surface temperature increment	dimensionless	(see table in excel sheet Slash&Burn)	(Slash&Burn)
319.	S&B_NutVolatFracP	Volatilization fraction of P in the burnt necromass, as function of soil surface temperature increment	dimensionless	(see table in excel sheet Slash&Burn)	(Slash & Burn)
320.	S&B_pHRecFrac	Daily recovery fraction of soil pH in the topsoil from its post-fire towards its pre-fire value	fraction	0.001–0.1 (.01)	Management/Slash and Burn
321.	S&B_PileUpFrac	Fraction of dead wood pile up after slash and burn event	fraction	0 – 1 (0.7)	Management/Slash and Burn

No.	Acronym	Definition	Dimensions	Range of value (Default value)	Input Section (Link location in Excel)
322.	S&B_PSorpRecFrac	Daily recovery fraction of the P_sorption in the topsoil from its post-fire towards its pre-fire value	fraction	0.001–0.1 (.01)	Management/Slash and Burn
323.	S&B_ScorchWRemFrac	Fraction of scorched wood removed after slash and burn event	fraction	0 – 1 (.3)	Management/Slash and Burn
324.	S&B_SlashDOY	A graphical input tabulating day of year at which slashing is performed	julian days	(see S&B_Slash-DOY graph)	Management/Slash and Burn
325.	S&B_SlashYear	A graphical input tabulating year at which slashing is performed	dimensionless	any integer value (100)	Management/Slash and Burn
326.	S&B_SOMBurnFrac	Fraction of all SOM pools in the topsoil (Layer 1) respired (C) or mineralized (N & P) as a function of soil surface temperature increment	dimensionless	(see table in excel sheet Slash&Burn)	Management/Slash and Burn
327.	S&B_SurfLitBurnFrac	Fraction of all surface litter respired (C) or mineralized (N & P) as a function of soil surface temperature increment	dimensionless	(see table in excel sheet Slash&Burn)	Management/Slash and Burn
328.	S&B_TimetoPileUp	Number of days between primary burn and pile up (redistribution across the zones) for a secondary burn	days	1 – 100 (15)	Management/Slash and Burn
329.	S&B_TimetoWoodRem	Number of days between primary burn and removal of scorched wood	days	1 – 50 (10)	Management/Slash and Burn
330.	S&B_TTempTol[Tree]	Maximum fire temperature that a tree can tolerate. Temperature above the value will induce tree mortality	^{0}C	40 – 90 (75)	(Tree Library/ Slash&Burn)
331.	S&B_WatRetRecFrac	Daily recovery fraction of soil water retention in the topsoil from its post-fire towards its pre-fire value	fraction	0.001 – 0.1 (0.005)	Management/Slash and Burn
332.	S&B_WetnessTempImp	Fractional reduction in fire temperature per unit of moisture content of the fuel	fraction	0 – 1 (.5)	Management/Slash and Burn
333.	S_BDBDRefDecay	Relative rate of decay of the bulk density, returning the surface infiltration rate toward S_SurfInfiltrPerKsatDef and the saturated hydraulic conductivity towards S_KSatDefV	day^{-1}	0 – 0.1 (.001)	Soil Structure
334.	S_C_RtStrucFormFrac	Fraction of contribution of crop root decay on root channels	fraction per m	(.1)	Soil Structure
335.	S_KSatDefVi	Saturated hydraulic conductivity of the soil in the absence of macropore structure, as derived from texture-based pedotransfer functions. Read and calculation from Wanulcas.xls. Input needed to run pedotranfer refer to the sheet pedotranfer	cm day^{-1}	1 – 500 (layer 1 = 319, layer 2 = 54, layer 3 = 45, layer 4 = 40)	(Soil Hydraulic)

No.	Acronym	Definition	Dimensions	Range of value (Default value)	Input Section (Link location in Excel)
336.	S_KsatHperVi	Ratio of saturated hydraulic conductivity in horizontal and vertical direction for layer i	dimensionless	0 – 5 (1)	Soil Structure/K Sat ratio
337.	S_KSatInitVi[Zone]	Saturated hydraulic conductivity of the soil at the macropore structure existing at the start of the simulation. Read and calculation from Wanulcas.xls. Input needed to run pedotranfer refer to the sheet pedotranfer	cm day^{-1}	1 – 500 (layer 1 = 319, layer 2 = 54, layer 3 = 45, layer 4 = 40)	(Soil Hydraulic)
338.	S_KSatVDeepSub	Saturated hydraulic conductivity of the soil below layer 4, determining the rate of vertical drainage from the soil column	cm day^{-1}	1 – 100 (20)	Soil Structure
339.	S_RelSurfInfiltrInit[Zone]	Surface infiltration rate at the start of the simulation relative to its default value	dimensionless	100 – 10000 (1000)	Soil Structure
340.	S_RelWormLiti	Relative impact of 'worms' (soil fauna) on increase of saturated hydraulic conductivity in each layer	dimensionless	0 – 1 (1, 0.6, 0.3, 0.1)	Soil Structure
341.	S_RelWormSurf	Relative impact of 'worms' (soil fauna) increase of infiltration rate of the soil surface	dimensionless	0 – 1 (1)	Soil Structure
342.	S_SoilStructDyn?	Switch determining dynamics of soil structure (0 = false, 1 = true) based on decay and re-creation of macropores by soil fauna above the texture-based default values	day^{-1}	0 or 1 (0)	Soil Structure
343.	S_SurfInfiltrPerKsatDef [Zone]	Ratio of surface infiltration and Ksat for the first soil layer in the default condition of the soil as defined by the pedotransfer function	dimensionless	25 – 10000 (25)	Soil Structure
344.	S_T_RtStrucFormFrac	Fraction of contribution of tree root decay on root channels	fraction per m	(.3)	Soil Structure
345.	S_WormsLikeLitMetab	Activity (in arbitrary units) of soil fauna (“worms'') per unit of organic inputs in the litter metabolic pool	m^2 kg^{-1}	0.00001 – 0.1 (.00001)	Soil Structure
346.	S_WormsLikeLitStruc	Activity (in arbitrary units) of soil fauna (“worms'') per unit of organic inputs in the litter structural pool	m^2 kg^{-1}	0.0000005 – 0.1 (.0000005)	Soil Structure
347.	S_WormsLikeSOMMetab	Activity (in arbitrary units) of soil fauna (“worms'') per unit of organic inputs in the SOM metabolic pool	m^2 kg^{-1}	0.000001 – 0.1 (.000001)	Soil Structure
348.	S_WormsLikeSOMStruc	Activity (in arbitrary units) of soil fauna (“worms'') per unit of organic inputs in the SOM structural pool	m^2 kg^{-1}	0.00000005 – 0.1 (.00000005)	Soil Structure
349.	T_ApplyFBA?[Tree]	Switch (1 = yes, 0 = no) to determine whether the allocation of biomass from the canopy to the wood (branches + stem) pools is governed by the fractal branching parameters (allometric equations).	dimensionless	0 or 1 (1)	Tree Parameters

No.	Acronym	Definition	Dimensions	Range of value (Default value)	Input Section (Link location in Excel)
350.	T_ApplyPalm?[Tree]	Switch (1 = yes, 0 = no) to determine whether the allocation of biomass to storage pool follows oil palm rule.	dimensionless	0 or 1 (0)	(Tree Library/Fruit)
351.	T_BarkThickness	Bark thickness to calculate target of latex content, the thickness is following the growth of the tree.	cm	0 – 1 (see graph)	Management/Latex Production
352.	T_BrownBast?	Switch (1 = yes, 0 = no) to determine whether the rubber tree infected by brownbast.	dimensionless	0 or 1 (0)	Management/Latex Production
353.	T_CanBiomInit[Tree]	Initial amount of biomass in tree canopy (leaf and small stems)	kg per tree	0 – 1 (0)	Tree parameters
354.	T_CanHMax[Tree]	Maximum height of tree canopy	m	0 – 15 (8.2)	(Tree Library/Canopy)
355.	T_CanMaintResp	Fraction of canopy biomass use for maintenance respiration	dimensionless	(0.001)	Management/Latex Production
356.	T_CanShape[Tree]	Factor determining in which part of the tree leaves are concentrated. A value of 1 gives an even spread of tree leaves over the alley, a higher value (eg 2) concentrates tree leaves above the hedgerow	dimensionless	0 – 2 (.567)	(Tree Library/Canopy)
357.	T_CanWidthMax[Tree]	Maximum tree canopy width, half the canopy width (radius).	m	0 – 10 (4.655)	(Tree Library/Canopy)
358.	T_ConcFruit[SiNut,Tree]	Nutrient concentration in fruit component	dimensionless	0 – 0.1 (N = .02, P = .002)	(Tree Library/N-P concentration)
359.	T_ConcGroRes[SiNut,Tree]	Nutrient concentration in carbohydrate reserves	dimensionless	0 – 0.1 (N = .01, P = .0005)	(Tree Library/N-P concentration)
360.	T_ConcLf[SiNut,Tree]	N concentration in leaf component of tree	dimensionless	0 – 0.1 (N = .0173, P = .0009)	(Tree Library/N-P concentration)
361.	T_ConcRt[SiNut,Tree]	Nutrient concentration in tree roots (only for Rt_ATType=2)	dimensionless	0 – 0.1 (N = .0122, P = .0006)	(Tree Library/N-P concentration)
362.	T_ConcTwig[SiNut,Tree]	Nutrient concentration in twig component of tree	dimensionless	0 – 0.1 (N = .00073, P = .0016	(Tree Library/N-P concentration)
363.	T_ConcWood[SiNut,Tree]	Nutrient concentration in wood component of tree	dimensionless	0 – 0.1 (N = .0047, P = .0008)	(Tree Library/N-P concentration)
364.	T_DiamBiom1[Tree]	Biomass of a tree of diameter 1 cm; Intercept (a) of allometric equation (Branch biomass = a StemDiameterb). Calculation from Functional Branch Analysis (FBA). Input needed to run FBA refer to tree parameterization	kg	0.01 – 1 (.6513)	(Tree Library/Allometric branching)

No.	Acronym	Definition	Dimensions	Range of value (Default value)	Input Section (Link location in Excel)
365.	T_DiamBranch1[Tree]	Intercept (a) of allometric equation (Tree branch biomass = a Diameterb). Calculation from Functional Branch Analysis (FBA). Input needed to run FBA refer to tree parameterization	kg	0.01 – 1 (.0334)	(Tree Library/Allometric branching)
366.	T_DiamCumLit1[Tree]	Cumulative litterfall expected for a stem diameter of 1 cm. Calculation from Functional Branch Analysis (FBA). Input needed to run FBA refer to tree parameterization	kg	0.01 – 1 (.0302)	(Tree Library/Allometric branching)
367.	T_DiamLfTwig1[Tree]	Intercept (a) of allometric equation (Leaf &Twigbiomass = a StemDiameterb). Calculation from Functional Branch Analysis (FBA). Input needed to run FBA refer to tree parameterization	kg cmb	0.01 – 1 (.9656)	(Tree Library/Allometric branching)
368.	T_DiamSlopeBiom[Tree]	Power coefficient (b) of allometric equation (Branch biomass = a StemDiameterb). Calculation from Functional Branch Analysis (FBA). Input needed to run FBA refer to tree parameterization	dimensionless	0 – 3 (2.0937)	(Tree Library/Allometric branching)
369.	T_DiamSlopeBranch[Tree]	Power coefficient (b) of allometric equation (Tree branch biomass = a Diameterb). Calculation from Functional Branch Analysis (FBA). Input needed to run FBA refer to tree parameterization	dimensionless	0 – 3 (2.4195)	(Tree Library/Allometric branching)
370.	T_DiamSlopeCumLit[Tree]	Power coefficient (b) of the alloemtric equation describing the increase of cumulative litterfall with stem diameter. Calculation from Functional Branch Analysis (FBA). Input needed to run FBA refer to tree parameterization	dimensionless	0 – 3 (3.0937)	(Tree Library/Allometric branching)
371.	T_DiamSlopeLfTwig[Tree]	Power coefficient (b) of allometric equation (Leaf&Twig biomass = a StemDiameterb). Calculation from Functional Branch Analysis (FBA). Input needed to run FBA refer to tree parameterization	dimensionless	1 – 3 (1.7270)	(Tree Library/Allometric branching)
372.	T_DiamTreshHarv[Tree]	Tree diameter of timber harvested	cm	100	Management/Timber Harvesting
373.	T_DOY 1 LfFlush[Tree]	Day of the first cycle of leaf flush	julian days	1 – 365 (1)	Tree parameters/Tree leaf phenology)
374.	T_DOY 2 LfFlush[Tree]	Day of the second cycle of leaf flush	julian days	1 – 365 (400)	Tree parameters/Tree leaf phenology
375.	T_DOY SeaLitFall1Start[Tree]	Day when the first season of leaf starts dropdown	julian days	1 – 365 (400)	Tree parameters/Tree leaf phenology
376.	T_DOY SeaLitFall2Start[Tree]	Day when the second season of leaf starts dropdown	julian days	1 – 365 (400)	Tree parameters/Tree leaf phenology

No.	Acronym	Definition	Dimensions	Range of value (Default value)	Input Section (Link location in Excel)
377.	T_DOY_Compl1LfFall[Tree]	Day when the first season of leaf completely dropdown	julian days	1 – 365 (400)	Tree parameters/ Tree leaf phenology
378.	T_DOY_Compl2LfFall[Tree]	Day when the second season of leaf completely dropdown	julian days	1 – 365 (400)	Tree parameters/ Tree leaf phenology
379.	T_DOYFlwBeg[Tree]	The earliest day in a year when tree start to flowers	julian days	1 - 365 (200)	(Tree Library/ Growth stage)
380.	T_DOYFlwEnd[Tree]	The latest day in a year when tree start to flowers	julian days	1 - 365 (250)	(Tree Library/ Growth stage)
381.	T_DynTapping Frac	Dynamic value of fraction of latex stock would be tapped everyday. The simulation will run using this dynamic value when T_BrownBast? switch to 1	dimensionless	See graph	Management/Latex Production
382.	T_ExpRetThresh	Threshold value of expected return to labour		(30)	Management/Latex Production
383.	T_FracSeaLitFall1[Tree]	Fraction of tree canopy become litterfall	dimensionless	0 – 1 (1)	(Tree parameter/ Tree leaf phenology)
384.	T_FruitAllocMax[Tree]	Allocation of biomass to fruit each day	kg m^{-2} day^{-1}	0 – 1 (0)	(Tree Library/Fruit)
385.	T_FruitAllocStage[Tree]	Graphical input parameter as a function of tree stage that determine how much fruit will produce from maximum fruit allocation	dimensionless	0 – 1 (see T_FruitAllocStage graph)	Management/Fruit Harvesting
386.	T_FruitHarvFrac[Tree]	Harvest index for fruit. Constant value for every fruiting season	dimensionless	0 – 1 (0)	Management/Fruit Harvesting
387.	T_FruitMoistFrac[Tree]	Standard moisture content for expressing marketable fruit of each tree	dimensionless	0 – 1 (0)	Profitability
388.	T_GenLitFracMax[Tree]	Fraction of fruit will drop	dimensionless	0 – 1 (.05)	Management/Fruit Harvesting
389.	T_GenLitStage[Tree]	Graphical input parameter as a function of tree stage that determine how many fruit will drop	dimensionless	0 – 1 (see T_GenLitStage graph)	Management/Fruit Harvesting
390.	T_GraphPhenol?[Tree]	Parameter governing an option to simulate tree phenology using graph. Value 0 means tree phenology using phenology parameters, value 1 means tree phenology using graph	dimensionless	0 or 1 (0)	Tree parameter/Tree leaf phenology
391.	T_GroMax[Tree]	Maximum growth rate of hedgerows at full canopy closure	kg m^{-2} day^{-1}	0 – 0.1 (.014)	(Tree Library/ Growth)

	No.	Acronym	Definition	Dimensions	Range of value (Default value)	Input Section (Link location in Excel)
	392.	T_GroResFrac[Tree]	Fraction of tree carbohydrate reserves converted to biomass during regrowth stage after pruning	day^{-1}	0 – 0.5 (.025)	(Tree Library/ Growth)
	393.	T_GroResInit[Tree]	Initial amount of tree carbohydrates as reserves of tree potential growth	kg per tree	0 – 1 (0.25)	Tree parameters
●	394.	T_GrowthResp			(1)	Management/Latex Production
●	395.	T_HeartWoodAllocAft-Pruned?	Parameter governing an option to simulate heartwood. Value 0 means after pruning no sapwood biomass that allocated to heartwood biomass, value 1 means after pruning all sapwood biomass allocated to heartwood biomass.	dimensionless	(0)	Tree parameter/Tree stem (sapwood & heartwood)
	396.	T_InitStage[Tree]	Initial stage of tree when it was planted. If tree already growing at the start of simulation, it is the stage at the start of simulation time	dimensionless	0 – 2 (0)	(Tree Library/Growth stage)
●	397.	T_KillDOY[Tree]	Schedule date, day of year to kill tree	julian days	1 – 365 (1)	Management/Killing Trees
●	398.	T_KillY[Tree]	Schedule date, year to kill tree	dimensionless	any integer value (1000)	Management/Killing Trees
	399.	T_KLight[Tree]	Tree canopy (leaves Wonent) extinction light coefficient = the efficiency of tree foliage in absorbing light	dimensionless	0 – 1 (.7)	(Tree Parameters/ Light Capture)
	400.	T_LAIMax[Tree]	Maximum value of LAI in the tree canopy	dimensionless	0 – 5 (4)	(Tree Library/ Canopy)
	401.	T_LAIMinMaxRatio[Tree]	Parameter describing canopy thickness/dense. Value 1 is maximum thickness	dimensionless	0 – 1 (1)	(Tree Library/ Canopy)
●	402.	T_LatexFormResp	Respiration for Latex formation		(0.01)	Management/Latex Production
●	403.	T_LatexMainResp	Fraction of latex production use for maintenance respiration	dimensionless	(0.0001)	Management/Latex Production
●	404.	T_LatexMoistFrac[Tree]	Standard moisture content for expressing marketable latex of each tree	dimensionless	0 – 1 (.14)	Profitability
●	405.	T_LatexRecoveryTime	Time for latex to recover.		(7)	Management/Latex Production
	406.	T_LifallDroughtFrac[Tree]	Fraction of tree biomass becomes litterfall due to drought	day^{-1}	0 – 1 (.01)	(Tree Library/Litterfall)

No.	Acronym	Definition	Dimensions	Range of value (Default value)	Input Section (Link location in Excel)
407.	T_LifallThreshWStress[Tree]	Threshold value for tree litterfall due to drought	dimensionless	0 – 1 (.7)	(Tree Library/Litterfall)
408.	T_LifallWeight[Zone,Tree]	Input weight value governing amount of tree litterfall going into each zone relative to other zones (eg. 1:1:1:1 means equal mulch given in each zones on area basis)	dimensionless	0 – 10 (1,1, 1, 1)	Litterfall
409.	T_LignLifall[Tree]	Lignin concentration of tree litterfall (eg. 20%=0.2)	dimensionless	0 – 1 (.43)	(Tree Library/Litter Quality)
410.	T_LignPrun[Tree]	Lignin concentration of pruned tree biomass (eg. 20%=0.2)	dimensionless	0 – 1 (.4)	(Tree Library/Litter Quality)
411.	T_LignRt[Tree]	Lignin concentration of tree root	dimensionless	0 – 1 (.4)	(Tree Library/Litter Quality)
412.	T_LWR[Tree]	Leaf Weight Ratio = leaf dry weight per unit shoot dry weight	dimensionless	0 – 5 (.494)	(Tree Library/ Growth)
413.	T_MaxBarkLatexContent	Maximum of latex content in bark	dimensionless	0 – 1 (0.3)	Management/Latex Production
414.	T_MaxGrowthUtFrac			(.2)	Management/Latex Production
415.	T_MaxUseFrac			(.1)	Management/Latex Production
416.	T_MemExpY	How much a farmer forget previous yield (latex yield) and use it as a basis for his expectation of future latex yield, value in 0 - 1. 0 = he remembers fully, 1 = he forgets fully	dimensionless	0 - 1 (0.1)	Management/Latex Production
417.	T_MinDiamforTappingcm[Tree]	Minimum tree diameter for tapping	cm	10 – 15 (15)	Management/Latex Production
418.	T_MycMaxInf[Tree]	Fraction of tree roots infected by mychorrhiza for a soil layer where the Rt_MTInfFrac parameter is 1	dimensionless	0 – 1 (.3)	(Tree Library/Mycorrhiza
419.	T_NFixDayFrac[Tree]	Fraction of current N deficit derived from atmospheric N_2 fixation per day for each tree if T_NFixVariable = 1 (('true')	day^{-1}	0 - 1 (.125)	(Tree Library/N Fixation)
420.	T_NFixDWMaxFrac[Tree]	Maximum fraction of the T_GroRes[Dw] pool that can be respired for N_2 fixation if T_NFixVariable = 0 (('false')	day^{-1}	0 - 0.5 (.05)	(Tree Library/N Fixation)
421.	T_NFixDWUnitCost[Tree]	Dry weight cost for respiration per unit N_2 fixation, if T_NFixVariable = 0 (('false')	kg [dw] g^{-1} [N]	0 – 1 (0)	(Tree Library/N Fixation)

No.	Acronym	Definition	Dimensions	Range of value (Default value)	Input Section (Link location in Excel)
422.	T_NfixResp[Tree]	Responsiveness of N_2 fixation to N stress (N in biomass divided by N target), if T_NFixVariable = 0 (('false')	dimensionless	0 – 5 (0)	(Tree Library/N Fixation)
423.	T_NFixVariable?[Tree]	Switch (0 = false, 1 = true) to choose between variable (N-stress dependent) versus constant N_2 fixation as fraction of N deficit	dimensionless	0 or 1 (0)	(Tree Library/N Fixation)
424.	T_NlifallRed[SiNut,Tree]	Reducing factor for nutrient concentration of tree litterfall which depend on type of tree	dimensionless	0 – 2 (.7 for N and P)	(Tree Library/Litterfall)
425.	T_NutMobT[SiNut]	Relative rate of transfer, per unit root length density (cm cm^{-3}), from the 'immobile' pool of nutrients to the 'mobile' or sorbed pool, due to Crop root activity	m^2 day^{-1}	0 – 0.02 (0)	(Tree Library/Root Impacts on Nutrient Mobility)
426.	T_PanelQuality1[Tree]	Bark available for tapping at the first period of tapping			Management/Latex Production
427.	T_PanelQuality2[Tree]	Bark available for tapping at the second period for tapping			Management/Latex Production
428.	T_PanelRecoveryTime	Recovery time of bark have been tapped that would be available for next period of tapping	days	(7300)	Management/Latex Production
429.	T_PlantDOY[Tree]	Schedule for date of planting time. Entered from Wanulcas.xls	julian days	1 – 365 (see table in excel sheet Tree Management)	(Tree Management)
430.	T_PlantY[Tree]	Schedule for year of planting time. Entered from Wanulcas.xls	dimensionless	any integer value (see table in excel sheet Tree Management)	(Tree Management)
431.	T_PolypLifall[Tree]	Polyphenol concentration of tree litterfall (eg. 3 %=0.03)	dimensionless	0 – 1 (0)	(Tree Library/Litter Quality)
432.	T_PolypPrun[Tree]	Polyphenol concentration of pruned tree biomass (eg. 3 %=0.03)	dimensionless	0 – 1 (0)	(Tree Library/Litter Quality)
433.	T_PolypRt[Tree]	Polyphenol concentration of tree root	dimensionless	0 – 1 (0)	(Tree Library/Litter Quality)
434.	T_PrunDoY[Tree]	Schedule for date of pruning. Entered from Wanulcas.xls	julian days	1 – 365 (365)	(Tree Management)
435.	T_PrunFracC[Tree]	Fraction of canopy that gets pruned, for T_PrunType = 0. Constant for every pruning	dimensionless	0 – 1 (0)	Managements/PruningEvents
436.	T_PrunFracC[Tree]	Fraction of tree canopy gets pruned, for T_PrunFrac? = 0	dimensionless	0 – 1 (1)	Management/PruningEvents

No.	Acronym	Definition	Dimensions	Range of value (Default value)	Input Section (Link location in Excel)
437.	T_PrunFracD[Tree]	Fraction of tree canopy that gets pruned, for T_PrunFrac? = 1	dimensionless	0 – 1 (1)	(Tree Management)
438.	T_PrunHarvFracC[Tree]	Fraction of pruned canopy that harvested (not return to the system), for T_PrunType? = 0. Constant for every pruning.	dimensionless	0 – 1 (0)	Managements/PruningEvents
439.	T_PrunHarvFracD[Tree]	Fraction of tree pruned biomass harvested. Value changes overtime	dimensionless	0 or 1 (0)	(Tree Management)
440.	T_PrunLimit	Critical total LAI of all trees shadowing the crop zone, triggering a pruning event	dimensionless	0 – 5 (100)	Management/PruningEvent
441.	T_PrunMoistFrac[Tree]	Standard moisture content for pruned biomass of each tree	dimensionless	0 – 1 (.14)	Profitability
442.	T_PrunPlant?[Tree]	Parameter governing pruning decision. 1 = tree is automatically pruned before crop planting, 0 = tree does not automatically pruned	dimensionless	0 or 1 (1)	Management/PruningEvent
443.	T_PrunRecov[Tree]	Time needed for tree to recover after pruning	days	0 – 30 (14)	Management/PruningEvent
444.	T_PrunStageLimit[Tree]	The latest crop stage at which automatic pruning is still performed. Corresponds to T_PrunPlant? = 1	dimensionless	1 – 2 (1.8)	Management/PruningEvent
445.	T_PrunType?	This parameter govern the type of pruning events. 0 = Pruning determined automatically based on canopy denseness (tree LAI). Associated with T_PrunLimit and Tree_StageLimit. 1 = Pruning determined by calender. Assciated with Pruning section in sheet Tree Management, Wanulcas.xls	dimensionless	0 (0 or 1)	Managements/PruningEvents
446.	T_PrunWeight[Zone,Tree]	Input weight value governing amount of tree pruning going into each zone relative to other zones (eg. equal pruned biomass given in each zones on area basis means 1:1:1:1)	dimensionless	0 – 10 (0, 1, 1, 1)	Management/PruningEvent
447.	T_PrunY[Tree]	Schedule for year of pruning. Entered from Wanulcas.xls	dimensionless	any integer value (100)	(Tree Management)
448.	T_RainWStorCap[Tree]	Rainfall intercepted by tree stored as thin film at leaf surface	dimensionless	(1)	(Tree Library/Rain Interception)
449.	T_RecoveryExp			(.01)	Management/Latex Production
450.	T_RelLatexFormPriority			(.7)	Management/Latex Production
451.	T_RelLightMaxGr[Tree]	Relative light intensity at which shading starts to affect tree growth	dimensionless	0 - 1 (.5)	(Tree Library/Light Capture)

No.	Acronym	Definition	Dimensions	Range of value (Default value)	Input Section (Link location in Excel)
452.	T_RelPosinZone[Tree]	Position of each tree within each zone; 0 means the position of the trees on the left side of its zone, 1 means on the right side of its zone.	dimensionless	0 – 1 (0)	(AF System)
● 453.	T_RestDayperTappingDay	Number of days between tapping event	days	(see T_RestDayper TappingDay)	Management/Latex Production
454.	T_RhizEffKaPT	Proportional reduction of the apparent adsorption constant for P due to root activity of the crop, expressed as fraction of N_KaPdef per unit tree root length density	m^2 day^{-1}	0 – .2 (0)	(Tree Library/Root impacts on P mobility)
455.	T_RtDiam[Tree]	Tree root diameter. It is used in calculating water and nutrient uptake. For all root type.	cm	.05 – 3 (.1)	(Tree Library/Roots)
● 456.	T_Rubber?	Switch (1 = yes, 0 = no) to determine whether the tree growth as rubber tree, there is allocation of biomass to latex pool	dimensionless	0 or 1 (0)	(Tree Library/ Growth)
● 457.	T_SapWoodScaling Rule	Power coefficient of conversion of diameter of sapwood to heartwood. Default value 1 means no increasing of diameter heartwood	dimensionless	0 – 1 (1)	Tree parameter/Tree stem (sapwood & heartwood)
458.	T_SLA[Tree]	Tree specific leaf area = tree leaf surface area per unit leaf dry weight	m^2 kg^{-1}	0 – 30 (7.87)	(Tree Library/ Growth)
● 459.	T_SlashLabour	Amount of labour involved in slashing the field per unit simulated filed as a function of biomass slashed	person days	(see T_SlashLab graph)	Management/Slash and Burn
460.	T_SlashSellWoodFrac[Tree]	Indicates the fraction of wood that is removed from the plot at the time of slashing the vegetation	dimensionless	0 – 1 (0)	Management/Slash and Burn
461.	T_StageAftPrun[Tree]	Tree growth stage after pruning	dimensionless	0 – 2 (1)	(Tree Library/Growth stage)
462.	T_Tapatall?	Switch (1 = yes, 0 = no) to determine whether the tree will tapped or not	dimensionless	0 or 1 (0)	Management/Latex Production
463.	T_TapGirthFraction	Fraction of girth for tapped	dimensionless	0.3 – 0.5 (0.5)	Management/Latex Production
464.	T_TappableHeight[Tree]	Maximum length of stem bark can be tapped	cm	100 – 150 (100)	Management/Latex Production
465.	T_TappDOW	Tapping day of work	days	380	Management/Latex Production
466.	T_TappingFrac	Constant value of fraction of latex stock would be tapped everyday	dimensionless	0 – 1 (0.5)	Management/Latex Production

No.	Acronym	Definition	Dimensions	Range of value (Default value)	Input Section (Link location in Excel)
467.	T_TappingFracMultiplier	Quick modification on dynamic value of fraction of latex stock would be tapped	dimensionless	(1)	Management/Latex Production
468.	T_TappingSlice	Bark thickness of tapping	cm	0.3 – 0.5 (0.35)	Management/Latex Production
469.	T_Temp2	Temperature for maintenance respiration	dimensionless	(see T_Temp2 graph)	Management/Latex Production
470.	T_TempRespMaint	A graphical relation between temperature and maintenance respiration	dimensionless	(see T_TempResp-Maint graph)	Management/Latex Production
471.	T_TimeGenCycle[Tree]	Length of generative cycles of tree	days	any integer value (150)	(Tree Library/Growth stage)
472.	T_TimeVeg[Tree]	Length of vegetative cycles of tree	days	any integer value (720)	(Tree Library/Growth stage)
473.	T_TranspRatio[Tree]	Amount of water needed per unit dry matter production of tree	l kg^{-1}	0 – 500 (300)	(Tree Library/Growth)
474.	T_TranspRatioTime	Graphical input parameter as a function of tree stage that determine the dynamic of tree transpiration per unit biomass production	-	-	Tree Parameter
475.	T_TreesperHa[Tree]	Tree plant density	dimensionless	any integer value (400)	(AF System)
476.	T_WoodBiomInit[Tree]	Initial amount of biomass in tree stem	kg per tree	0 – 1 (0)	Tree Parameters
477.	T_WoodDens[Tree]	Wood density of each tree species	kg m^{-3}	(750)	(Tree Library)
478.	T_WoodFracHRemain	Wood height remain after pruning. If you do not want to harvest wood/timber when pruning makes sure this is a high value, eg. 100.	m	0-100 (100)	Management/Pruning Events/Other Pruning Parameters
479.	T_WoodHarvDOY[Tree]	Schedule for date of pruning. Entered from Wanulcas.xls	julian days	1 – 365 (364)	(Tree Management)
480.	T_WoodHarvFrac[Tree]	Fraction Harvested wood	dimensionless	0 – 1 (.95)	Management/Timber Harvesting
481.	T_WoodHarvY[Tree]	Schedule for year of timber harvesting. Entered from Wanulcas.xls	dimensionless	Any integer value (100)	(Tree Management)
482.	T_WoodHInit[Tree]	Initial value of tree bare stem height (tree height excluded canopy)	m	0 – 15 (0)	Tree Parameters

No.	Acronym	Definition	Dimensions	Range of value (Default value)	Input Section (Link location in Excel)
483.	T_WoodMaintResp	Fraction of wood biomass use for maintenance respiration	dimensionless	(0.000001)	Management/Latex Production
484.	T_WoodMoistFrac[Tree]	Standard moisture content for expressing marketable wood of each tree	dimensionless	0 – 1 (0)	Profitability
485.	Temp_AType	A number governing type of soil temperature data used in the simulation(0= constant value of soil temperature , 1 =read from monthly average data,2=read from daily data which is read from external file)	dimensionless	1, 2 or 3 (1)	Soil Temperature
486.	Temp_Cons	Soil temperature throughout the simulation; corresponds to Temp_AType=0	0^C	15 – 40 (28)	Soil Temperature
487.	Temp_DailyData	Actual daily data of soil temperature; corresponds to Temp_AType=2. Read from Wanulcas.xls	0^C	(see table in excel sheet weather)	(WEATHER)
488.	Temp_DailyPotEvap	Daily potential evaporation. Entered from Wanulcas.xls	mm day^{-1}	(see table in excel sheet weather)	(WEATHER)
489.	Temp_EvapPotConst	Amount of water evaporating from top soil in absence of plant cover	mm day^{-1}	0 – 10 (3)	Soil Evaporation
490.	Temp_MonthAvg	Monthly average of soil temperature; corresponds toTemp_AType=1. Entered as graphical function	0^C	(see Temp_MonthAvg graph)	Soil Temperature
491.	Temp_PotEvapConst?	Parameter governing type of soil evaporation potential data. 1 = constant throughout simulation, 0 = daily data, 2 = monthly data based on thornthwaite calculation	dimensionless	0 or 1 (1)	Soil Evaporation
492.	TW_DrivenEnergyEpot?	Switch (1 = yes, 0 = no) to determine whether the tree water demand driven by Epot	dimensionless	(0)	Soil Evaporation
493.	TW_PotSuctAlphMax[Tree]	Plant potential where transpiration is (1-Alpha)*potential transpiration, where Alpha is a small value (e.g. 0.01)	cm	-7000 – -3 000 (-5000)	(Tree Library/Water Uptake)
494.	TW_PotSuctAlphMin[Tree]	Plant potential where transpiration is Alpha*potential transpiration, where Alpha is a small value (e.g. 0.01)	cm	-30000 – -10000 (-15000)	(Tree Library/Water Uptake)
495.	W_FieldCapkCriti[Zone]	Field capacity determined by a threshold rate of subsequent drainage (Kcrit) that is set in the pedotransfer worksheet; the actual field capacity used is the maximum of this value and the field capacity derived from the height above a groundwater table. Read and calculation from Wanulcas.xls (pedotransfer). Input needed to run pedotransfer refer to the sheet pedotransfer	m^3 water m^{-3} soil	(see table in excel sheet Soil Hydraulic)	(Soil Hydraulic)

No.	Acronym	Definition	Dimensions	Range of value (Default value)	Input Section (Link location in Excel)
496.	W_Hyd?	Parameter governing water hydraulic lift application in model. 1= apply hydraulic lift in overall water balance, 0=otherwise	dimensionless	0 – 1 (0)	Run & Output Section
497.	W_HydEqFraction	Fraction of water hydraulic lift	fraction	(.1)	Soil Water and Nutrient
498.	W_PhiPxi[Zone]	Graphs showing relationship between pressure head in i-th soil layer of each zone and matrix flux potential (the index x refers to the plants with the highest (H), lowest (L), medium-high (MH) or medium low (ML) rank of root water potential), but the graphs will be identical. Read and calculation from Wanulcas.xls (pedotransfer). Input needed to run pedotranfer refer to the sheet pedotranfer	cm^2 day^{-1}	(see table in excel sheet Soil Hydraulic)	(Soil Hydraulic)
499.	W_PhiThetai[Zone]	Matrix flux potential at a given theta/soil water content in layer I of each zone. Read and calculation from Wanulcas.xls (pedotransfer). Input needed to run pedotranfer refer to the sheet pedotranfer	cm^2 day^{-1}	(see table in excel sheet Soil Hydraulic)	(Soil Hydraulic)
500.	W_PThetai[Zone]	Graphs showing relationship between volumetric soil water content and pressure head in i-th soil layer of each zone. Read and calculation from Wanulcas.xls (pedotransfer). Input needed to run pedotranfer refer to the sheet pedotranfer	cm	(see table in excel sheet Soil Hydraulic)	(Soil Hydraulic)
501.	W_ThetaInacci[Zone]	Amount of volumetric soil water in i-th soil layer of each zone not available for plant. It is value of volumetric soil water at pF= 4.2 or P = -16000. Read and calculation from Wanulcas.xls (pedotransfer). Input needed to run pedotransfer refer to the sheet pedotrasnfer	$l\ m^{-2}$ day^{-1}	(see table in excel sheet Soil Hydraulic)	(Soil Hydraulic)
502.	W_ThetaIniti[Zone]	Initial volumetric soil water content related to water saturated pore volume in i –th soil layer of each zone. Current values are 1, 0.9, 0.8, 0.7 for layer 1…4, respectively	fraction	0 – 1	Soil Water and N/ Initial Soil Water
503.	W_ThetaPi[Zone]	Graphs showing relationship between pressure head in i-th soil layer of each zone and volumetric soil water content. Read and calculation from Wanulcas.xls (pedotransfer). Input needed to run pedotransfer refer to the sheet pedotransfer	cm	0 – 0.5 (see table in excel sheet Soil Hydraulic)	(Soil Hydraulic)
504.	W_ThetaPMax[Zone]	Volumetric soil water content at a given maximum soil potential at top layer. Read and calculation from Wanulcas.xls (pedotransfer). Input needed to run pedotransfer refer to the sheet pedotransfer	cm	(see table in excel sheet Soil Hydraulic)	(Soil Hydraulic)

Appendix 8. Statistical criteria for model evaluation result according to Loague and Green (1991)

Criterion	Symbol	Calculation formula	Range	Optimum
Maximum error	ME	$Max\lvert P_i - O_i\rvert_{i=1}^{n}$	≥ 0	0
Root mean square	RMSE	$\left(\sum_{i=1}^{n}\frac{(P_i - O_i)^2}{n}\right)^{\frac{1}{2}} * \frac{100}{O_{mean}}$	≥ 0	0
Coefficient of determination	CD	$\frac{\sum_{i=1}^{n}(Oi - O_{mean})^2}{\sum_{i=1}^{n}(P_i - O_{mean})^2}$	≥ 0	1
Modelling efficiency	EF	$\frac{\left(\sum_{i=1}^{n}(Oi - O_{mean})^2 - \sum_{i=1}^{n}(P_i - O_i)^2\right)}{\sum_{i=1}^{n}(Oi - O_{mean})^2}$	≤ 1	1
Coefficient of residual mass	CRM	$\frac{\left(\sum_{i=1}^{n}Oi - \sum_{i=1}^{n}P_i\right)}{\sum_{i=1}^{n}O_i}$	≤ 1	0

P_i = predicted values, O_i = observed values, n = number of samples and O_{mean} is the mean of the observed data.

Appendix 9. Other Useful parameters and their definition (parameters which can be input or output which are not yet at users interface layer)

No	Acronym	Definition	Dimensions	Default value	Model Sector
1.	C_GroResMobFrac	Fraction of crop growth reserves that is remobiilze into yield and root component	dimensionless	0.95	Crop Growth
2.	C_NDemand	Amount of Nitrogen or Phosphorus demanded by crop per day; for a crop biomass less than 2 Mg/ha demand is based on 5% N, above that (after canopy closure) on 1% N	kg ha^{-1}	output	Crop Growth
3.	C_NUptTot	Total amount of Nitrogen or Phosphorus in all soil layers potentially available for crop uptake per day	g m^{-2}	output	Crop Growth
4.	CW_DemandAct	Actual amount of crop water demand per day. Potential demand reduced by plant water potential.	l m^{-2}	output	Crop Water
5.	CW_UptTot	Total amount of water uptake by crop from all soil layers per day in each zone	l m^{-2}	output	Crop Water
6.	C_SeedConc[PlantComp]	Nutrient concentration on seed. Value for DW =1, N = 0.05 and P = 0.005	-	see definition	Crop Growth
7.	Evap_Surf	Amount of water evaporates from top soil per day in each zone	l m^{-2}	output	Soil Evaporation
8.	GHG_GWP_CH4	Global Warming Potential for CH4. Global Warming potential is the warming effect of a trace gas on the atmosphere. It differs between trace gases due to different atmospheric lifetime and different heat absorption capacity. It is expressed per molecule basis relative to CO2	-	15	GHG & Denitrification
9.	GHG_GWP_NO2	Global Warming Potential for NO2	-	310	GHG & Denitrification
10.	Mc_LitterC	Amount of carbon in dead plant biomass	g m^{-2}	output	Litter C
11.	Mn_LitterNInpN [Zone,SiNut]	Amount of Nitrogen or Phosphorus in litter layer	g m^{-2}	output	Litter N
12.	N_ExchLittLay1 [Zone,SiNut]	Mineralisation Nitrogen or Phosphorus in litter layer	g m^{-2}	output	N Layer 1
13.	N_SomMini Exch [Zone,SiNut]	Mineralisation of Nitrogen or Phosphorus in soil layer i	g m^{-2}	output	N Layer 2-4
14.	Rt_CLrvt	Crop root growth as a function of time	cm cm^{-3} day^{-1}	output	Crop Root
15.	S_BDEqPower	Power coefficient (b) of the allometric equation describing the decreasing of bulk density later effect on surface infiltration and saturated hydraulic conductivity	dimensionless	0.5	Soil Structure Dynamic
16.	T_BiomAllTrees	Total amount of aboveground biomass for all trees	kg m^{-2}	output	Tree Growth

No	Acronym	Definition	Dimensions	Default value	Model Sector
17.	T_HarvPrunCum[Tree]	Total pruned tree biomass harvested	kg m^{-2}	output	Tree Growth
18.	T_LifallCum[Tree]	Cumulative amount of tree litterfall	kg m^{-2}	output	Tree Growth
19.	T_PrunCum	Cumulative amount of tree pruned biomass	kg m^{-2}	output	Tree Growth
20.	T_WatStressMem	A parameter influencing the effect of drought on litterfall.	-	0.75	Tree Water Parameter
21.	TF_AbRelSizePow[Tree]	Input parameter in oil palm module	-	2	Tree Fruit
22.	TF_AvgDWpFruit[Tree]	Average dry weight of oilpalm fruit	kg m^{-2}	-	Tree Fruit
23.	TF_FemSinkperBunch	Graphical input parameter in oil palm module as a function of fruit stage	-	-	Tree Fruit
24.	TF_FirstBudtoFlowerInit [Tree]	Number of phyllochron time units before sex determination during flower development	-	25	Tree Fruit
25.	TF_InitFruitpBranch [Tree]	Input parameter in OilPalm module	-	500	Tree Fruit
26.	TF_MaleSinkperBunch	Graphical input parameter in oil palm module as a function of fruit stage	-	-	Tree Fruit
27.	TF_MaleThresh[Tree]	Input parameter in OilPalm module	-	0.17	Tree Fruit
28.	TF_MTrresptoWStress[Tree]	Input parameter in OilPalm module	-	0	Tree Fruit
29.	TF_Phyllocrontime[Tree]	Input parameter in oil palm module	-	15	Tree Fruit
30.	TF_PhysAgeInit[Tree]	Phyllochron age at time of planting or start of simulation. Input parameter in oil palm module	-	15	Tree Fruit
31.	TF_StageAbortSens	Graphical input parameter in oil palm module as a function of fruit stage	-	-	Tree Fruit
32.	TF_WatStressAbortFrac[Tree]	Input parameter in OilPalm module	-	0.1	Tree Fruit
33.	TW_Alpha	A small value determing plantt maximum and minimum transpiration. Plant potential for maximum transpiration'(TW_PotSuctAlphMax, unit in cm) is defined as (1- TW_Alpha)*potential transpiration and plant potential for minimum transpiration'(TW_PotSuctAlphMin, unit in cm) is defined as TW_Alpha*potential transpiration.	-	0.1	Tree Water
34.	TW_AxResFactor	For a 10 m distance and a demand of 5 mm day-1 we expect the need for an additional gradient of 2.5 bar = 2500 cm; the factor is thus 5/250 = 0.02	-	0.02	Tree Water
35.	TW_L	Coefficient related to tree root conductivity	cm day^{-1}	10^{-5}	Tree Water
36.	TW_PotSuctBuff	Hydrostatic gradient to overcome transport resistance in wet soil l	cm	0.05	Tree water parameter
37.	W_PMax	Maximum value of soil potential in positive value	cm	0	Water layer 1
38.	W_SeepScalar	A constant that determine how much water will infiltrate to the deeper soil layer when soil water content go beyond field capacity.	fraction	0	Water layer 1...4

Appendix 10. Rainfall simulator within WaNuLCAS 4.0

WaNuLCAS, like many other hydrological and ecological models, needs daily rainfall data as input. Such a dataset is however not always readily available or reliable because, for example due to high cost of buying the daily data from a professional weather record institution, equipment failure or human error in reading the daily rainfall amount from installed equipment in the field or rainfall records that tend to accumulate rainfall over several days so wet and dry days tend to be clumped together. Some research also needs an extrapolation of rainfall events, e.g. for simulations of hydrological process over one or more 30 years climate scenario windows into the future for specified global circulation models and climate change scenarios.. An appropriate method to generate daily rainfall data is thus necessary. The common ('Markov chain') way to generate daily rainfall basically consists of two steps: i) simulating rainfall occurrence, i.e. determining whether or not a day is a rainy day or not, and ii) for rainy days, determine the amount of rainfall.

Determining whether or not a day is a rainy day

Rainfall occurrence is usually simulated by one of two types of Markov chain model. One is a two-state (wet, dry) Markov chain where the order (first, second or third) indicates the number of preceding days that influences the probability that the next day is a rainy day or not. Another is a multi-state first-order Markov chain. The commonest is the two-state first-order Markov chain describing probability for four rainfall occurrences: probability that today and previous day are wet P(W|W), probability that today is wet and the previous day was dry P(W|D), probability that today is dry and the previous day was wet P(D|W), and probability that both today and previous day are dry P(D|D). Usually the definition for a wet day is that the rainfall amount exceeded 1 mm.

If a month consists of n days then there will be n-1 consecutive days in that month. Among n-1 pairs, some are W|W, W|D, D|W, and/or D|D. Suppose that $n_{w|d}$ describes the number of consecutive day where the current day is wet while the previous day was dry, then:

Estimate of $P(W|D) = \frac{n_{w|d}}{n_{w|d} + n_{d|d}}$ **[A11]**

The same principle applies for calculating P(W|W), P(D|W), and P(D|D), and:

$n_{w|w} + n_{w|d} + n_{d|w} + n_{d|d} = n-1$
P(W|W) + P(D|W) = 1
P(W|D) + P(D|D) = 1
P(W|W) ≥ P(W|D)

Now supposed that the first day in a generated sequence is dry, then we would predict that the next day is dry if 0<r<P(D|D) and wet if P(D|D)<r<1 where r is a generated random number between 0 and 1. If the first day is wet then the next day is dry if 0<r<P(D|W) and it is wet if P(D|W)<r<1. The two-state first–order Markov chain can be expanded, e.g. up to the second or third-order to determine a rainy day. In that case, a larger transition matrix has to be produced. In the two states second-order Markov chain, there will be 2^2x2 rainfall occurrence probabilities, in the third-order 2^3x2. For these higher orders of Markov chain, the same principle applies to determine whether a day is a rainy day or not, e.g. if it happened that three consecutive days were dry, then the next day is dry if $0<r<P(D|DDD)$ and wet when $P(D|DDD)<r<1$.

For the first-order Markov chain, there is a relation between P(W|D) and f which is the average fraction of days that are wet in a month or in other words, the overall probability of a day being rainy (Geng *et al*., 1986):

$$P(W|D) = bf \qquad \textbf{[A12]}$$

They found empirically that the constant b has a value of around 0.75. f must equal the sum of the products of the two conditional probabilities and the probability of either a dry or wet day:

$$f = bf(1-f) + P(W|W)f \qquad \textbf{[A13]}$$

Thus, the relation between P(W|W) and f is:

$$P(W|W) = 1 - b + bf \qquad \textbf{[A14]}$$

This means that regardless the value of f, P(W|W) is always 1-b greater than P(W|D).

Remarks:
In case we only have data of the fraction of wet days in a month (i.e. f value), P(W|W) and P(W|D) can be calculated by assuming b equals 0.75 which seems to be a common value for many tested areas. If variation in rainfall occurrence is high between months, the calculation of rainfall occurrence probabilities can be done for each month.

In a multi-state Markov chain model, daily rainfall is divided into a number of states. For example, Boughton (1999) defined state 1=no rainfall, 2=0<rain<0.9 mm, 3=0.9<rain<2.9 mm, and so on up to state 6=14.9 mm<rain with no upper limit. A transition matrix will describe the probability for rain in one state to be followed by rain on the next day in the same or another state.

Determining the amount of rainfall in a wet day

The most common approach for describing the distribution of rainfall amounts on days with rain is to ignore the serial autocorrelation and consider that rainfall amounts are serially independent and to fit some theoretical distributions to the precipitation amount (Duan et al, 1995). This means we assume that precipitation amounts on subsequent rainy days are independent but that the probability of it being a rainy day may depend on the state of the previous day(s). If a day is wet then we need the second step, i.e. to estimate the rainfall amount in that day. There are many different probability distribution functions that can be used for this purpose and they are classified into single-parameter models and multi-parameter models. Some single-parameter models have been derived by calibrating multi-parameter models.

Single-parameter models

The exponential distribution is probably the most widely used single-parameter model of daily rainfall for its simplicity and relatively good fit (e.g. Richardson, 1981). Its cumulative distribution function is as follow where x is the daily precipitation, λ=E(x) is expectation of daily precipitation in a month obtained by dividing the monthly rainfall by number of wet days, and F(x) is the probability of events with rainfall amount less than x:

$$F(x) = 1 - e^{\frac{-x}{\lambda}} \qquad \textbf{[A15]}$$

Pickering et al. (1988) calibrated the three-parameter beta-P distribution model to yield a single-parameter model as follow:

$$F(x) = 1 - (1 + \tfrac{x}{9\lambda})^{-10} \qquad \textbf{[A16]}$$

A member of Weibull family of distribution can also be a single-parameter model (Rodiguez, 1977), with c as a dimensionless parameter with a value usually around 0.75 or 0.5 (Selker and Haith, 1990) and Γ is the complete (two-parameter) Gamma function:

$$F(x) = 1 - \exp\left\{-\left[\Gamma\left(1 + \tfrac{1}{c}\right)\tfrac{x}{\lambda}\right]^{c}\right\} \qquad \textbf{[A17]}$$

If the threshold for a wet day is 1 mm, then equation 7 needs to be modified to (Scotter *et al*., 2000):

$$F(x) = 1 - \exp\left\{-\left[\Gamma\left(1 + \tfrac{1}{c}\right)\tfrac{(x-1)}{(\lambda-1)}\right]^{c}\right\} \qquad \textbf{[A18]}$$

It can be shown that a smaller value of c will generate more extreme rainfall events. The most important however is to correctly describe the probability of high daily rainfall events (e.g. rainfall > 20 mm). Solving equation 8 for x gives:

$$x = \left[\frac{\lambda-1}{\Gamma\left(1+\frac{1}{c}\right)}\right][1 - \ln(1 - F)]^{\frac{1}{c}} + 1 \qquad \textbf{[A19]}$$

Multi-parameter models

This model type is generally considered to describe the distribution of precipitation amounts better than the single-parameter models because of greater flexibility obtained with the larger number of parameters. The 2-parameter Gamma, 3-parameter Gamma, and 3-parameter mixed exponential have been used. Richardson (1982) stated that unless the mixed exponential distribution has a clear advantage over the 2-parameter Gamma distribution, the gamma distribution is an appropriate choice of models for most applications. The general form of 2-parameter Gamma probability function is as follow:

$$f(x) = \frac{x^{\alpha-1}e^{\frac{-x}{\beta}}}{\beta^{\alpha}\Gamma(\alpha)} \qquad \textbf{[A20]}$$

And the cumulative distribution function is:

$$F(x) = \frac{\gamma(\alpha, \frac{x}{\beta})}{\Gamma(\alpha)} \qquad \textbf{[A21]}$$

Where $\gamma(\alpha, x/\beta)$ is the lower incomplete Gamma function. There are two ways for estimating α and β which are constant in the Gamma distribution function. The simplest but good one uses moment estimators (Devore, 1987):

$$E(x) = \alpha\beta \qquad \textbf{[A22]}$$

$$Var(x) = \alpha\beta^2 \qquad \textbf{[A23]}$$

To estimate rainfall amount in a wet day, we again have to generate a random number between 0 and 1 and put this value equals to F (i.e. the cumulative distribution function). Equation 5 will give a value for x, i.e. the rainfall of the day according to an exponential distribution, equation 6 according to beta-P distribution, equation 9 with Weibull-type distribution, and equation 11 according to 2-parameter Gamma distribution. For equation 9, MS Excel has a GAMMALN(x) function to return a value of natural logarithm of Gamma function $\Gamma(x)$. For equation 11, the function GAMMAINV (F,α,β) in MS Excel can return the inverse of Gamma cumulative distribution.

Appendix 11. Water uptake module in WaNuLCAS

Water transport from soil to leaf has to overcome resistances along the pathway (Smith *et al.*, 2004). Uptake of water is compatible with the physical reality of driving forces (gradients in water potential) and resistances in the path: bulk soil – rhizosphere – root – leaf – atmosphere (De Willigen et al., 2000). When plants open the stomata, a negative water potential in the leaves can generate flow of water towards the leaves from all layers of soil where the plant has roots and where the water potential in the soil is less negative than that in the plant. Water transport can be modeled as an Ohm's law analogue and requires the calculation of gradients in water potential and conductivity (the inverse of resistance) on different sections along the pathway. The water uptake module only pertains to a part of the path, i.e. the transport of water from bulk soil to stem base. Below is a description of modeling water uptake in the WaNuLCAS model.

I. Plant level

The calculation of water potential and transport is done at voxel and plant level. Voxel-level calculation involves roots and water inside the voxels only, whereas plant-level calculation integrates uptake and transport over rooted voxels.

1. Soil water potential perceived by plant (Ψ^{sp}, cm)

$$\Psi^{sp} = -\left(\frac{\sum_i Lrv_i * v_i}{\sum_i Lrv_i * v_i * \left|\Psi_i\right|^{-d}}\right)^{1/d} \qquad \textbf{[A24]}$$

Where:
Lrv_i = root length density in voxel i (cm cm^{-3})
v_i = voxel volume (cm^3)
Ψ_i = soil water potential in voxel i (cm)
d = indicates the relative influence of dry voxels ('drought signal') on the calculation of Ψ^{sp}. When d=1, we use a harmonic average (dimensionless). The lower the value of d the more negative Ψ^{sp} and the lower the transpiration demand due to the closure of stomata.

Ψ^{sp} should be between the Ψ of driest and wettest soil. The resulting unit = cm cm^{-3} * cm^3 / (cm cm^{-3} * cm^3 * cm-1) = cm

2. Rhizosphere potential (Ψ^{rhizp}, cm)

$$\Psi^{rhizp} = \Psi^{sp} * (1 + b) \qquad \textbf{[A25]}$$

Where:
b = buffer potential: potential drop needed for water to move from bulk soil to the root surface (in the rhizosphere), here expressed as a fraction of Ψ^{sp} (%)

3. Potential gradient for uptake (radial transport into roots) (Ψ^{radp}, cm)

$$\Psi^{radp} = \frac{-E^{pot} * 0.1}{K^{rad} * Lra} \qquad \textbf{[A26]}$$

Where:

E^{pot} = potential transpiration demand (liter m^{-2} or mm). In the WaNuLCAS model (Van Noordwijk *et al.*, 2004), E^{pot} is calculated as light intercepted by plant * dry matter production per unit light interception * water use efficiency (or water use per unit dry matter production). E^{pot} is an input value of the water uptake module.

K^{rad} = radial conductivity: the inverse of resistance involved in radial movement of water from the root surface to xylem per unit gradient in water potential and per unit path-length (cm^3_{water} $cm^{-1}_{gradient\ of\ water\ potential}$ $cm^{-1}_{root\ length}$)

Lra = total root length per unit soil surface area (cm cm^{-2})

The resulting unit = mm * 0.1 / (cm^3 cm^{-1} cm^{-1} * cm cm^{-2}) = cm

4. Potential gradient for longitudinal transport in roots (Ψ^{longp}, cm)

$$\Psi^{longp} = -E^{pot} * \frac{\sum_i L_i * Lrv_i * v_i}{\sum_i Lrv_i * v_i} * R^{longsap} \qquad \textbf{[A27]}$$

Where:

L_i = distance from voxel midpoint to soil surface (stem base) (m)

$R_{longsap}$ = longitudinal resistance factor for root sap (root to stem base): gradient in water potential per unit water demand per unit path-length ($cm_{gradient\ of\ water\ potential}$ $mm^{-1 water\ demand}$ m^{-1}_{soil})

The resulting unit = mm * (m * cm cm^{-3} * cm^3 / cm cm^{-3} * cm^3) * cm mm^{-1} m^{-1} = cm

5. Initial estimate of required plant water potential (Ψ^{lrepq}, cm) to meet the potential transpiration demand

$$\Psi^{reqp} = \Psi^{rhizp} + \Psi^{radp} + \Psi^{longp} = \Psi^{sp} * (1+b) + \Psi^{radp} + \Psi^{longp} \qquad \textbf{[A28]}$$

It can be noted that, only Ψ^{radp} and Ψ^{longp} are a function of Epot. Ψ^{rhizp} is independent on transpiration demand. On the other hand, the former two are not dependent on soil water condition.

II. Plant level (reduced transpiration demand)

The actual transpiration is assumed to be a function of the potential transpiration demand (that depends on 'external' environmental factors only) and the plant water potential.

6. Campbell reduction factor for transpiration (f, dimensionless) is calculated from a sigmoid-type function.

$$f = \frac{1}{1+\left(\frac{\Psi_{reqp}}{\Psi_{0.5}}\right)^{a}} \qquad \textbf{[A29]}$$

$$a = \frac{2*\ln\left(\frac{\alpha}{1-\alpha}\right)}{\ln\left(\frac{\Psi_{\max}^{transp}}{\Psi_{\min}^{transp}}\right)} \qquad \textbf{[A30]}$$

Where:

$\Psi_{0.5}$ = plant water potential where transpiration is half of its potential value (cm)
a = Campbell factor (dimensionless)
α = a small value (dimensionless, default is 0.1)
Ψ^{trasp}_{max} = plant water potential when f is at (1 - α) (cm)
Ψ^{trasp}_{min} = plant water potential when f is at α (cm)

Because:

$$1-\alpha = \frac{1}{1+\left(\frac{\Psi_{\max}^{transp}}{\Psi_{0.5}}\right)^{a}} \qquad \textbf{[A31]}$$

And:

$$\alpha = \frac{1}{1+\left(\frac{\Psi_{\min}^{transp}}{\Psi_{0.5}}\right)^{a}} \qquad \textbf{[A32]}$$

Then:

$$\Psi_{0.5} = -\sqrt{\Psi_{\max}^{transp} * \Psi_{\min}^{transp}} \qquad \textbf{[A33]}$$

7. Reduced plant transpiration demand and water potential

$$E^{red} = E^{pot} * f$$ **[A34]**

$$\Psi^{redreqp} = \Psi^{rhizp} + \left(\Psi^{radp} + \Psi^{longp}\right) * f$$ **[A35]**

Recalling that only Ψ^{radp} and Ψ^{longp} are a function of E^{pot}, Ψ^{rhizp} is independent on transpiration demand.

III. Voxel level

Water uptake by the root system is 'scaled-up' from the calculation of water uptake for a single root. This has been described in e.g. De Willigen *et al*. (2000), De Willigen and Van Noordwijk (1987, 1995), Heinen (2001), and Personne *et al*. (2003).

8. Voxel rhizosphere water potential$_i$ (Ψ^{rhiz}_i cm)

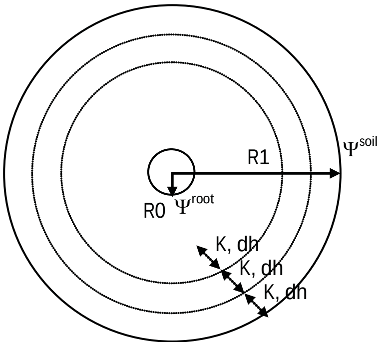
$$\Psi_i^{rhiz} = \Psi^{redreqp} - \frac{L_i}{\left(\dfrac{\sum_i^n L_i * Lrv_i * v_i}{\sum_i^n Lrv_i * v_i}\right)} * f * \Psi^{longp}$$ **[A36]**

The resulting unit = cm – (m * m^{-1}) * cm = cm

In other words, the plant water potential at stem base applies for $L_i = 0$. The equation shows that Ψ^{rhiz}_i reflects the potential needed for water transport from the soil towards root surface and that required for water to flow to root xylem.

9. Potential water transport$_i$ (T^{pot}_i, mm)

This should be understood as flow of water from the bulk of soil towards root surfaces. For this, we need information of pressure head difference, water conductivity across the bulk soil (i.e. strongly dependent on soil characteristic) and path length. The flow equations for soil water transport are however highly non-linear (De Willigen *et al*., 2000) due to the non-linear relationship between water content and potential, and conductivity is decreasing strongly with decreasing pressure head. Consider the following figure that illustrates 'space grids' for soil-root radial transfer within soil cylinder:



Roots are assumed to be vertically oriented and regularly distributed in the voxel. Root is regarded to be a cylinder shape situated within soil cylinder. The bulk soil of the voxel is then divided into uniform (i.e. the same size) vertical soil cylinders with single root inside each of them. Water transport for single root only occurs between the inner boundary (root surface) and the outer boundary (i.e. soil cylinder). R0 is the root radius (cm) and R1 is the radius of soil cylinder (cm) that depends on root length density in the voxel:

$$R1 = \frac{1}{\sqrt{\pi * Lrv}} \quad \text{[A37]}$$

Water potential at the root surface (root-soil contact) is the voxel rhizosphere water potential (Ψ_{root}), at the bulk soil (i.e. at the outer boundary) is the soil water potential (Ψ_{soil}). Soil is usually drying closer to the root surface. Therefore, Ψ_{soil} and conductivity should be calculated for each 'space grid' (where linearity could be assumed) along bulk soil-root path. Because root is vertically oriented within soil cylinder, only radial water transport to root surface is taken into account. For horizontal transport, the non-linearity of the flux can be removed by introducing the matric flux potential (De Willigen et al., 2000):

$$\Phi = \int_{h_{ref}}^{h} K * dh \quad \text{[A38]}$$

Where Φ is the matric flux potential (cm^2 day^{-1}), h_{ref} is a reference value of the pressure head (cm), and K is water conductivity (cm day^{-1}). For the water flux from soil towards the root surface (i.e. for condition that $\Psi_{root} < \Psi_{soil}$ for the transport to occur):

$$\Delta\Phi = \int_{h^{root}}^{h^{soil}} K * dh = \int_{h^{ref}}^{h^{soil}} K * dh - \int_{h^{ref}}^{h^{root}} K * dh = \Phi^{soil} - \Phi^{root} \quad \text{[A39]}$$

In the WaNuLCAS model, for a discretisation of the integral, h_{ref} is obtained at pF = 6 and the 'space grids' pertain to 0.1 intervals of pF down to pF^{soil} and pF^{root}:

$$h(pF) = -10^{pF} \quad \textbf{[A40]}$$

$$K(h) = K_{sat} * \frac{\left(\left(1+\left|alpha*h\right|^{n}\right)^{1-\frac{1}{n}} - \left|alpha*h\right|^{n-1}\right)^{2}}{\left(1+\left|alpha*h\right|^{n}\right)^{\left(1-\frac{1}{n}\right)*(\lambda+2)}} \quad \textbf{[A41]}$$

$$\Phi_i^{soil} = \sum_{j=pF_i^{soil}}^{j=pF^{ref}} [(K(h(j)) + K(h(j+0.1))] * 0.5 * (h(j) - h(j+0.1)) \quad \textbf{[A42]}$$

$$\Phi_i^{root} = \sum_{j=pF_i^{root}}^{j=pF^{ref}} [(K(h(j)) + K(h(j+0.1))] * 0.5 * (h(j) - h(j+0.1)) \quad \textbf{[A43]}$$

Where alpha, K_{sat}, λ, n are Van Genuchten parameters. $\Delta\Phi$ reflects water flow per unit area of root surface. ‘Scaling up’ to a root system requires information of R0 and R1 to consider the circumference of root and soil bulk cylinder, and of root length density. The steady rate solution to the flow problem (i.e. the same flux rate to root surface regardless of the depth of the root segment in the voxel) and assuming that all roots have a good contact with soil, is assumed to be the potential water transport from soil to roots in the voxel (mm day^{-1}) (Heinen, 2001; De Willigen and Van Noordwijk, 1995):

$$T_i^{pot} = \frac{\pi * \Delta z_i * Lrv_i * (\Phi_i^{soil} - \Phi_i^{root}) * \left(\rho_i^2 - 1\right) * 10^3}{G_0(\rho_i)} \quad \textbf{[A44]}$$

$$G_0\left(\rho_i\right) = \frac{1}{2}\left(\frac{1-3\rho^2}{4} + \frac{\rho^4 \ln(\rho)}{\rho^2 - 1}\right) \quad \textbf{[A45]}$$

$$\rho_i = \frac{R1_i}{R0} \quad \textbf{[A46]}$$

Where Δz is the voxel thickness (m). It can be noted that $\Delta\Phi$ should be multiplied by total root length (i.e. Lrv * voxel volume) to get the volume of water flow (cm^3). Division by voxel surface area results length of water and thus only the voxel thickness is included in the equation. Now suppose we have two types of plant (model extension into several plants is surely possible): weak (i.e. with less negative plant water potential) and strong plant, and assume $\Phi^{soil} > \Phi^{weak} > \Phi^{strong}$. Water flux for weak and strong plant (say 'common range') is Φ^{soil} - Φ^{weak} and exclusively for strong plant ('exclusive range') is Φ^{weak} - Φ^{strong}. The potential water transport of weak and strong plant in the voxel is calculated as follow:

For weak plant:

$$T_i^{potweak} = \frac{\pi * \Delta z_i * Lrv_i^{weak} * (\Phi_i^{soil} - \Phi_i^{weak}) * \left((\rho_i^{com})^2 - 1 \right) * 10^3}{G_0(\rho_i^{com})}$$

[A47]

$$\rho_i^{com} = \frac{R1_i^{com}}{R0_i}$$

[A48]

$$R1_i^{com} = \frac{1}{\sqrt{\pi * (Lrv_i^{weak} + Lrv_i^{strong})}}$$

[A49]

$$D0_i = \left(\frac{Lrv_i^{weak} * \sqrt{D0^{weak}} + Lrv_i^{strong} * \sqrt{D0^{strong}}}{Lrv_i^{weak} + Lrv_i^{strong}} \right)^2$$

[A50]

$$R0_i = \frac{D0_i}{2}$$

[A51]

For strong plant in the common range:

$$T_i^{potstrong} = \frac{\pi * \Delta z_i * Lrv_i^{strong} * (\Phi_i^{soil} - \Phi_i^{weak}) * \left((\rho_i^{com})^2 - 1 \right) * 10^3}{G_0(\rho_i^{com})}$$

[A52]

And for strong plant in the exclusive range:

$$T_i^{potstrong} = \frac{\pi * \Delta z_i * Lrv_i^{strong} * (\Phi_i^{weak} - \Phi_i^{strong}) * \left((\rho_i^{ex})^2 - 1 \right) * 10^3}{G_0(\rho_i^{ex})}$$

[A53]

$$\rho_i^{ex} = \frac{R1_i^{ex}}{R0_i} \qquad \text{[A54]}$$

$$R1_i^{ex} = \frac{1}{\sqrt{\pi * Lrv_i^{strong}}} \qquad \text{[A55]}$$

(As said before, the described modeling of potential transport is actually limited to the case where roots are regularly distributed and vertically oriented with a complete root-soil contact. For the time being, it also approximates potential transport in a more complex situation, i.e. non-regularly distributed and parallel roots or non-regularly distributed and non-parallel roots either with complete or non-complete root-soil contact whilst maintaining model simplicity (Van Noordwijk, personal communication). However, complete soil-root contact along the whole length of a root may be the exception rather than the rule (De Willigen and Van Noordwijk, 1987). Due to the assumptions, water transport potential is usually non-limiting (see below) for the actual water uptake).

10. Available water for uptake (θ_i, mm)

Available water in the common and exclusive range respectively are:

$$\theta_i^{com} = \left(\theta_i^{soil} - \theta_i^{weak}\right) * \Delta z_i * 10^3 \qquad \text{[A56]}$$

$$\theta_i^{ex} = \left(\theta_i^{weak} - \theta_i^{strong}\right) * \Delta z_i * 10^3 \qquad \text{[A57]}$$

Following Van Genuchten:

$$\theta_i^{soil} = \frac{\left(\theta_i^{sat} - \theta^{residual}\right)}{\left(1 + \left|alpha_i * \Psi_i^{soil}\right|^{ni}\right)^{1 - \frac{1}{n_i}}} + \theta^{residual} \qquad \text{[A58]}$$

Where Ψ^{soil} is replaced by Ψ^{weak} and Ψ^{strong} to calculate θ^{weak} and θ^{strong} respectively. In the common range, water is shared between the weak and strong plant proportional to their root length density. Next is the calculation for weak plant with the same principle applies for strong plant:

$$\theta_i^{comweak} = \frac{Lrv_i^{weak}}{Lrv_i^{weak} + Lrv_i^{strong}} * \theta_i^{com} \qquad \text{[A59]}$$

11. Adjusted water transport potential (T^{adjpot}_i, mm)

Water uptake is limited either by transport or water available for uptake. The minimum of the two say ‘adjusted water transport potential’ is then (calculated for the weak and strong plant in the common range, and for strong plant in the exclusive range):

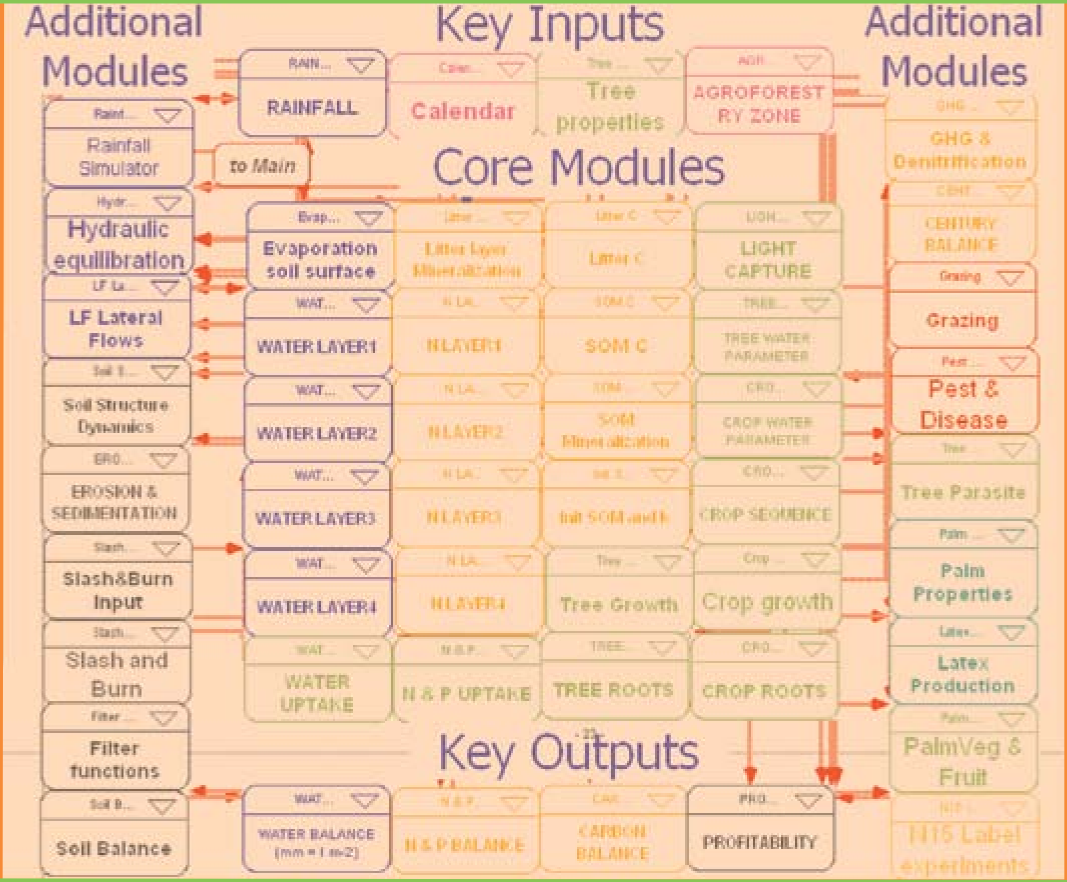
$$T_i^{adjpot} = \min\left(T_i^{pot}, \theta_i\right) \quad \textbf{[A60]}$$

12. Actual water uptake$_i$ (S_i, mm)

(The following calculation applies for the weak and strong plant)

If $\sum_i T_i^{adjpot} \leq E^{red}$ then $S_i = T_i^{adjpot}$ else **[A61]**

$$S_i = \frac{T_i^{adjpot}}{\sum_i T_i^{adjpot}} * E^{red} \quad \textbf{[A62]}$$



World Agroforestry Centre
TRANSFORMING LIVES AND LANDSCAPES